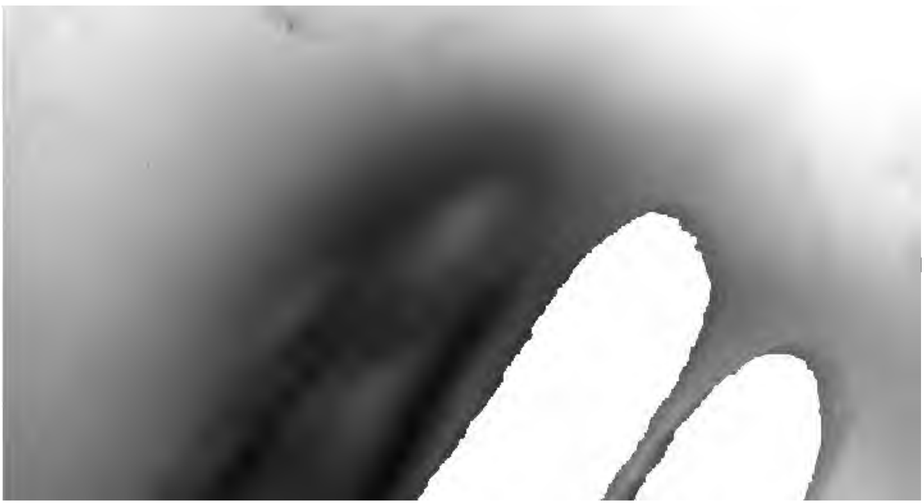

The Refractive and Motor Mechanism of the Eye

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PART I

PRINCIPLES OF OPTICS

CHAPTER I

VISION AND LIGHT

Vision is the sense which reveals to us the form and color of objects by the action of light on the retina; in other words, vision may be defined as the consciousness which results from the stimulation of the retina by light.

The visual apparatus consists of two distinct parts. The first of these is the eye, which is analogous to a photograph camera. The retina, which receives and transforms the light energy into a nerve impulse, corresponds to the sensitized plate of the camera. The second part of the visual apparatus consists of the optic nerve and its brain connections—the conducting and interpreting mechanism—by means of which the nerve impulse is carried to the visual areas of the brain and thence to the centers of consciousness, where the impulse is manifested as vision.

It falls within our province in this work to deal only with the former part of this apparatus—to study the eye as an optical contrivance and to investigate the adaptability and the imperfections of its mechanism.

Light, the physical agency by which we see, is a form of energy. The science of physics teaches that ultimately all energy is ***one,*** but that by the various modifications which it undergoes different results are manifested from its expenditure.

Light may be produced in various ways, as by mechanical or chemical action. Although light artificially produced plays an important part in our life, our chief source of light must always be the sun.

The study of the laws of light constitutes the science of *optics*. In its various branches this is a comprehensive study, which would lead us far beyond the province of ophthalmology.

Only a small part of the science of optics can, therefore, be considered in this work—that part which pertains to the *reflection* and, more especially, to the *refraction* of light.

A substance which has the power of developing light-energy, or emitting light, is said to be *luminous*. Thus the sun is a luminous body. On the other hand, the moon, which does not originate light, but only transmits it by reflection from the sun, is a non-luminous body.

Theories of the Transmission of Light.—The question as to the manner in which light is conveyed from a luminous body to the eye has given rise to two hypotheses, which are known, respectively, as the *corpuscular or emission theory and the wave theory.*

The corpuscular theory naturally presented itself to the ancients and was universally accepted prior to the development of the science of optics. In accordance with this theory, it was believed that light was a substance given off from a luminous body and that this substance was propelled in all directions in straight lines. *Sir Isaac Newton* was an advocate of this, in opposition to the second hypothesis (which was announced by *Huygens* in 1678), because, in the form in which the latter was then propounded, it failed to explain certain phenomena.

The second hypothesis, or *wave theory,* as enunciated by Huygens and as modified by subsequent investigators, satisfactorily explains all the observed phenomena of light. In fact, certain phenomena which follow as a necessary sequence of the wave theory were discovered through study of this theory, the mathematical demonstrations which led to such discoveries having afterward been corroborated by actual experiment.

Ether is the extremely tenuous matter which, *it has been assumed,* exists throughout the universe. It is only by the assumption that such matter exists that we can form a conception of the transmission of waves through space. There is no other evidence, except this mental requirement, that such matter really exists.

A familiar example of a wave is afforded by throwing a stone into a body of still water. In this case and in sound-waves traveling in air a vibratory motion of the particles of the conductor takes place in the direction in which the wave is moving. The earlier advocates of the wave theory of light naturally

supposed that in light-waves the method of vibration was similar to that of sound-waves, and since certain phenomena could not be explained under such conditions, the wave theory was abandoned for a century and a half, to be again brought into prominence by *Fresnal* (1815), who introduced the assumption that the vibratory motion in light-waves was transverse to the direction of wave motion. With this modification, all the observed phenomena of light are explainable. But this assumption cannot be accepted as excluding longitudinal vibrations, for a spherical wave can advance only in the directions in which vibratory disturbance is taking place. We must conclude, therefore, that light advances by means of longitudinal disturbances upon which is superposed a transverse disturbance, and that to the latter are due certain characteristic phenomena which are explainable only by means of such vibrations.

The exact nature of the vibratory disturbances which give rise to light is unknown; it was formerly supposed that there was a to-and-fro movement of the particles of the conductor *(ether)*, just as there is in sound-waves, but our conception of waves has been greatly broadened by the introduction by *Maxwell* of the electro-magnetic theory of wave conduction. In the transmission of electricity, a certain unknown change *(polarization)* takes place in the particles of the conductor. These particles become charged with energy, which they transmit to the adjoining particles and so on. Each particle, having transmitted its energy, returns to its original state and is again charged by particles behind it, and so the process continues. Since these changes occur in rhythmical impulses or pulsations, they constitute waves. Doubtless the transmission of light is similar to that of electricity—in fact, it is practically certain that light differs from electricity only in the shorter wave-length and more rapid vibration of the former.

Recent experiments in electricity have led *Professor Thomson*, of Cambridge, to return to the propulsion theory in a modified form. Whatever may be the nature of the corpuscles or *electrons* demonstrated by Professor Thomson, their existence is insufficient evidence for denying the theory of rhythmical impulses (waves) of electricity and light—a theory which has hitherto been found indispensable in the explanation of many phenomena.

As with the ear, only waves within certain limits are pro-

ductive of sound, so also the constitution of the eye is such that waves within certain limits of periodicity excite vision, while similar waves, whose oscillatory period is not within these limits, do not produce this sensation.

Color.—It can be shown with the aid of a prism, which causes a separation of waves according to their period of oscillation, that sunlight is composed of a number of waves of varying periodicity and wave-length (the latter being inversely proportional to the former), and that other waves also accompany the various waves of light. Certain waves whose vibratory period is too rapid to affect the retina as light manifest themselves by their power of causing chemical action; while others, whose vibratory period is too slow to affect the retina as light, are manifested as heat.

The various colors which we are able to distinguish depend upon this variation of vibratory period. While a number of theories have been put forward in explanation of color sensation, the scheme propounded by the great physicist, *Dr. Thomas Young* (1801), and afterward elaborated by *Helmholtz* is the most satisfactory. According to this theory the various light-waves are divided into three groups: (1) Those of least, (2) those of intermediate and (3) those of greatest rapidity of vibration. Each of these groups of waves has its distinctive action upon the retina. Waves comprised in the first group cause the color *red* to be seen; those in the second group are productive of *green*, and those in the third, or most rapid group, give rise to the sensation of *blue (violet)*.* These three, *red, green* and *blue*, are the three *primary colors*—not because there are only three sets of waves (the division of light into these groups being, of course, arbitrary), but because of the limitations of the eye.

So far this hypothesis accords well with the phenomena of color vision, but in the further endeavor to explain how these three groups of waves act differently upon the retina serious difficulties are encountered. It is assumed that there are three sets of terminal elements, one set for each group of waves, and that each set contains a characteristic photo-chemical substance which is affected predominantly by the group of waves to which it is adapted, while the other waves affect this substance in a

* Opinions differ as to whether blue or violet should be regarded as the primary color.

minor degree only. Many arguments have been advanced against this assumption, but it remains more plausible than any of the other hypotheses which have been offered.

Our color perception, however, is not limited to these three elementary sensations, for by the simultaneous stimulation in varying proportions of the three sets of elements other color sensations are afforded. When a screen is placed so as to intercept in a darkened room a beam of sunlight which has passed through a prism an observer may count on the screen six colors, clearly distinct, but merging gradually into the contiguous colors. These six colors are called the *colors of the spectrum.* They are *red, orange, yellow, green, blue,* and *violet.* To these *Newton* added a seventh color, *indigo,* between blue and violet.

Orange and yellow, lying between red and green, result from stimulation of the retina, in proper proportion, by the waves which give rise to the sensation of red together with those which give rise to green, but with little or no stimulation by the violet-producing waves, the latter waves having been eliminated in some way from the light which enters the eye. On the other hand the variations of color as seen in the spectrum lying between green and violet are the result of stimulation of the retina by those waves which produce green, together with those which produce violet, but with little or no stimulation by the red-producing waves. When all three groups of waves simultaneously stimulate the retina and without predominance of any one group, *whiteness* results.

One must not infer, however, from the foregoing brief description of the *Young-Helmholtz theory* of color perception that there is a sharp border line between the three groups of waves which form the visible spectrum. For instance, those waves of the second (intermediate) group which approximate in periodicity the first group (red waves) must act partly as red-producing waves; and similarly those waves which approximate the blue-producing waves must to some extent give rise to the sensation of blue.

We see, therefore, that the complete spectrum is formed by a multiplicity of waves, whose rapidity of vibration gradually increases, beginning with the ultra-red and extending through the visible spectrum to the chemical waves beyond the violet margin. In the visible part of the solar spectrum there are seen at various

intervals gaps or black lines (*Fraunhofer lines*) which show that certain waves have been destroyed. The discovery of these lines has led to the important study of spectrum analysis, for it has been learned that the absence (*absorption*) of certain waves is characteristic of the gaseous substances through which light has passed, and that from the number and position of such lines the chemical composition of these substances can be determined.

Velocity of Light, Wave Length, Vibratory Period.—It has been found from astronomical calculations and also from terrestrial experiments, that light travels through air and through space at the rate of 300,000,000 meters (approximately) or 186,000 miles a second.

The wave length at various parts of the spectrum has also been determined by very delicate experiments. The length of the red wave, near the beginning of the visible spectrum, is about $\frac{1}{1300}$ *mm*, and for violet, near the terminus, the wave length is about $\frac{1}{2500}$ *mm*. Hence, the wave length for light is embraced within these limits. Since light travels through space at the rate of 300,000,000,000 *mm* a second, it is apparent that for the first wave length there must be 390 million-millions of these wave lengths or vibrations in a second, and for the last, 750 million-millions of vibrations a second.

Luminosity.—By this term we denote the intensity of the sensation which results from retinal stimulation. *Yellow* is the color of greatest intensity. The sensation of brightness or of *light* seems to be in a measure independent of color, for when the illumination is very feeble, one may be able to detect light and yet be unable to assign to it any color. Similarly when the illumination is very powerful no distinction of color can be made. This is explained in the *Young-Helmholtz* hypothesis by assuming that in the former case there is not sufficient excess of stimulation of any one group of elements to make its color predominate, and in the latter case by assuming that all three sets of elements are so greatly stimulated that whiteness results.

Wave Front.—A luminous point emits light in all directions. If the rate of motion is the same in all directions, the wave front will evidently be spherical. In any meridian, as in the plane of the paper in diagrammatic representations, the wave front will be represented by a circle (Fig. 1).

It is a matter of common observation that light *travels in*

homogeneous media in straight lines—that is, it does not bend around corners as sound does. This fact was formerly thought to be inconsistent with the wave theory, but it has been proved that the bending must diminish with the diminution of the wave length. As compared with sound waves, the length of light waves is almost infinitesimal and, consequently, the bending of light waves must be ordinarily inappreciable; but it can be proved

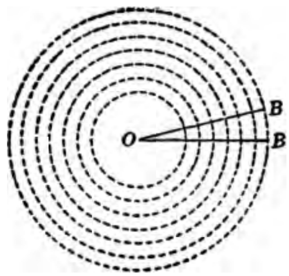


FIG. 1

experimentally that light bends around corners to an extent commensurate with its wave length. The shadow cast by a wire placed in the path of light is less than the actual geometrical shadow, which shows that the light has to a slight extent curved around the borders of the wire. The study of this phenomenon, called *diffraction,* constitutes an important branch of optics.

We see by inspection of Fig. 2 that the nearer the eye is to the source of illumination the greater is the portion of the

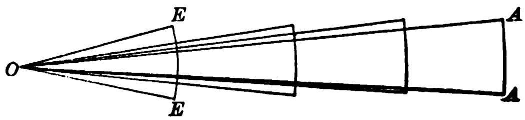


FIG. 2

wave which will enter the eye. Hence, the luminosity diminishes with the increase of distance of the luminous body. It is also apparent that the curvature of the wave front diminishes with the increase of distance. When the radius $O\ A$ is so great that the portion of the wave $A\ A$ may be regarded as a straight line, the wave is said to be *plane*.

Pencils and Rays.—A small portion of a wave, such as is represented in the section $B\ O\ B$ (Fig. 1) is called a *pencil.* An

infinitesimal pencil is called a *ray*. The lines OA and OE (Fig. 2) represent rays. A ray of light is therefore represented by a straight line perpendicular to the wave front.

A pencil which proceeds from a point, as from the center O, or which is directed towards a point, is said to be *homocentric*. We shall learn later in our studies that owing to certain disturbing factors, pencils may lose their homocentric character.

Superposition of Waves.—We do not ordinarily have to deal with mere points of light, but with objects of appreciable size. Spherical waves proceed from every point of a luminous object. Hence, we must infer that many waves may traverse the same space at the same time without destroying one another. This is known as the *principle of superposition;* it has its analogue in the superposition of motions. An object acted upon simultaneously by two forces will be displaced by each force as if the other had not acted, and the resultant displacement will be the same as if the object had first been displaced by one and subsequently by the other force. Just as it is possible that these two forces may act in opposition so as to neutralize each other, so is it possible that light-waves of a certain length (color) may be destroyed by other waves of the same length acting in opposition to the first. In this way (by the destruction of certain waves) objects assume their characteristic color, although illuminated by sunlight, which contains all the colors. It is by the production of an experimental *interference* of light-waves that the wave-lengths for the different colors have been determined.

Formation of Images.—In order that objects may be seen, it is necessary that images of these objects shall be depicted upon the retina. For the formation of an image it is essential that light from any point of the object shall reach a corresponding point on the intercepting screen, and that light from all other parts of the object shall be excluded from this point.

A very simple way of accomplishing this result is illustrated in Fig. 3, in which SS represents an opaque diaphragm having a small aperture at O. Light from A passes through the aperture and falls upon the screen at A_1. Light from other parts of AB cannot reach A_1, and, therefore, the luminous point A is reproduced at A_1. Similarly B_1 is a reproduction of B, and likewise the intermediate points of A_1B_1 are reproductions of the corresponding points of AB, and A_1B_1 is an inverted image of AB.

Since only a very minute pencil of light can be allowed to pass through the aperture in the diaphragm without blurring of the image, the illumination of the image is comparatively feeble, but there is another way by which a considerably larger pencil can be utilized to illuminate the image. It is by what is known as *refraction.*

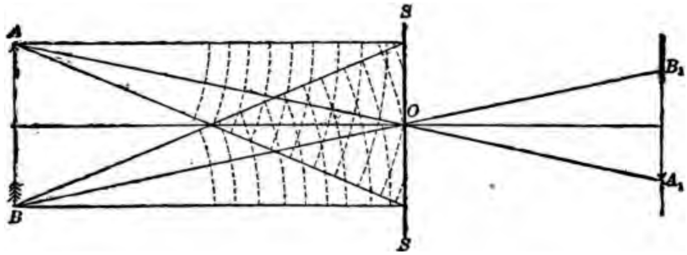


FIG. 3

The phenomenon of refraction is utilized by Nature in the production of vision, and the eye is constructed in conformity with the laws of refraction. To this branch of optics, therefore, we must chiefly devote our attention in the following chapters.

The following authorities have been consulted in the preparation of the foregoing chapter:

Gage, *Elements of Physics.*
Ganot, *Physics.*
Fresnal, *Théorie de la Lumière.*
Huygens,*Tractatus de Lumine.*
Maxwell, *Electricity and Magnetism.*
Preston, *Theory of Light.*
Thomson, J. J., *Electricity and Matter.*
Newton, *Opticks.*
Helmholtz, *Optique Physiologique.*
Tscherning, *Physiologic Optics.*
Mills, *Psychology of the Visual Act,* Posey and Spiller's *Eye and Nervous System.*
Thomson and Weiland, *Normal Color Perception,* Norris and Oliver's *System of Diseases of the Eye.*
Young, *Theory of Light and Colors.*

CHAPTER II

THE LAWS OF REFRACTION AND REFLECTION; REFRACTION AND REFLECTION AT PLANE SURFACES

A transparent substance—a substance which freely permits the passage of light through it—is called a *medium*.

A substance which does not permit the passage of light through it is said to be *opaque*.

When light, traversing one medium, meets another of different density some of the light is transmitted to the second medium and some of it continues, with its direction changed, in the first medium.

When the second medium offers some resistance to the passage of light, a certain portion of the incident wave is converted into some other form of energy. The part of the light energy so transformed, being lost as light, is said to be *absorbed*.

Many substances which, in thin layers, are transparent, offer such resistance to the passage of light that only a small part of an incident wave can pass through thick strata of these substances. On the other hand, a substance which under ordinary circumstances appears to be opaque, may not be entirely so when placed in the path of light of great intensity.

A substance which permits the passage of some light, but in such a diffused condition that objects cannot be seen through it is said to be *translucent*.

The difference between a transparent and an opaque body lies in the structural peculiarity of the substance. A common illustration of this difference is afforded by ice or glass, each of which is transparent in (thin) homogeneous layers but is opaque in a crushed or pulverized condition. The opacity in the latter state is due to the presence of air between the particles of denser

material. Because of the resulting heterogeneity of the structure the wave is so disturbed by reflection at each of the many surfaces that its penetrating power is lost.

The Law of Refraction.—Of the two chief portions of an incident wave let us first turn our attention to that portion which passes into the second medium. We learn from common observation that objects undergo an apparent displacement when we view them lying in a body of water. This displacement results from a change in the course of the rays which takes place at the surface of the water. This change of direction is called *refraction* (from *refrangere, to break*), because the path of the rays is *broken* or altered.

Refraction is therefore the change of direction which rays of light undergo when they pass from one medium to another of different density.

Willebrod Snell, of Leyden, is accredited as the discoverer of the *law of refraction* (1621). He did not, however, publish the result of his researches, and as this law was more fully explained by *Des-Cartes* (1637), it is often called by his name. It was *Des-Cartes* who first formulated it in the terms commonly used, as follows: *The incident ray, the refracted ray, and the normal (perpendicular) to the surface lie in a common plane; the incident and the refracted ray lie on opposite sides of the normal; and the sine of the angle of incidence bears a constant ratio to the sine of the angle of refraction.*

The angle of incidence is the angle which the incident ray makes with the normal to the surface ($N S R$) and the angle of refraction is the angle which the refracted ray makes with the normal ($N_1 S R_1$) (Fig. 4).

If we denote the angles of incidence and refraction by i and r respectively, the law of refraction is expressed by the equation

$$\frac{\sin i}{\sin r} = n.$$

The constant ratio n is called the *refractive index.**

Snell deduced this law by recording the results of many experiments. He knew nothing of the wave theory of light, of which the law of refraction is a necessary sequence, for the constant n represents the relative velocity of light in the two media,

*We shall subsequently learn that the refractive index varies with the color of the light. Unless it is otherwise specified, the refractive index refers to the average index, or that for yellow light.

the velocity being less as the density is greater. The refractive index has been determined for various substances with reference to air, the index of the latter being regarded as unity.

The indices of the substances with which we are chiefly con-

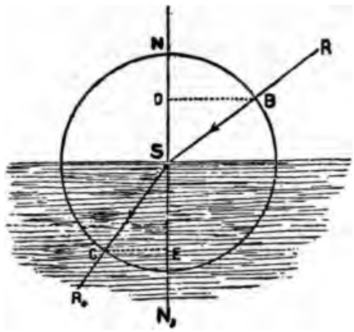


FIG. 4

The diagram of *Des-Cartes* illustrating the law of refraction. The sine of the angle of incidence is expressed by $\frac{DB}{SB}$; the sine of the angle of refraction by $\frac{EC}{SC}$. Since $SB = SC$, DB bears a constant ratio to EC.

cerned are as follows: Water, 1.33; glass, from 1.5 to 1.7; cornea, 1.377; aqueous and vitreous humors of the eye, 1.337; crystalline lens, 1.437 (approximately). The denser the substance the higher is the index, as a rule.

If the indices of two media with reference to air are denoted by n, and n_1, respectively, the index for the two media with reference to each other is expressed by $\frac{n_1}{n}$ and the formula of refraction becomes

$$\frac{\sin i}{\sin r} = \frac{n_1}{n}.$$

The sine of an angle increases with the angle, and therefore when n_1 is greater than n the angle of incidence $(N S R)$ is greater than the angle of refraction $(N_1 S R_1)$. This must be so in order to preserve the constant ratio in the foregoing equation.

Similarly, if n_1 is less than n the angle of incidence must be less than the angle of refraction.

We have therefore the following rule: When light passes *from a rarer to a denser medium* the rays are deflected *towards* the normal to the surface, and when it passes *from a denser to a rarer medium* the rays are deflected *away* from the normal. The

formula for refraction also shows that the deviation of a ray increases or diminishes as the angle of incidence increases or diminishes, for the sine of an angle increases less rapidly than the angle, and the more so according as the angle is greater. Therefore in order to maintain the constant ratio $\frac{n_1}{n}$, the greater angle (whether this is the angle of incidence or refraction) must increase more rapidly than the smaller angle. Consequently the difference between these two angles (which represents the deviation of the ray) must increase with an increase of the angle of incidence.

This brings us to the consideration of the ray which meets the surface perpendicularly. In this case, in which the angle of incidence is zero, the angle of refraction must likewise be zero. Therefore, *the ray which meets the surface perpendicularly undergoes no refraction.*

Passage of Light through a Medium bounded by Two Parallel Surfaces.—Rays of light passing through such a body and reentering the first medium, undergo no change of direction. This is illustrated in Fig. 5, in which *S R* represents a ray passing

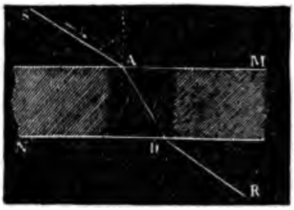


FIG. 5

through the medium *M N*. Since the two refracting surfaces are parallel, the normals at *A* and *D* are parallel. The angle of refraction at the first surface must therefore be equal to the angle of incidence in the second refraction, and consequently the second angle of refraction is equal to the first angle of incidence. In other words, the two deviations exactly neutralize each other, and there is no change of direction of the ray; but there is a lateral displacement of every ray except that which is perpendicular to the surfaces.

Prisms

A prism is a wedge-shaped portion of material bounded by two plane surfaces meeting in an edge. The angle included

by these two faces is called (in optics) the *refracting angle*. A plane which is perpendicular to the edge, and consequently to each face of the prism, is called a *principal plane* of the prism. At right angles to any principal plane—that is, in the direction of the edge of the prism—the two faces are parallel to each other.

Refraction of Parallel Rays by a Prism.—A ray of light passing through a prism whose refractive index is greater than

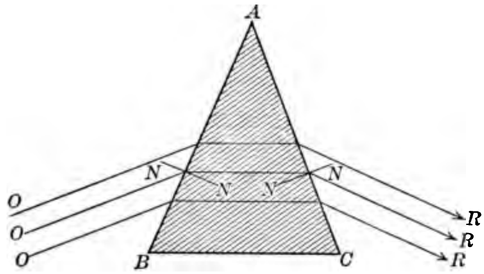


FIG. 6

that of the surrounding medium will always be deviated *away* from the apex or edge of the prism. In Fig. 6 $B\ A\ C$ represents a principal section or plane of a prism, and $O\ R$ represents any one of a series of parallel rays passing through the prism in this plane. At the first surface the rays, on entering the dense medium, are refracted towards the normal to this surface, and at the second surface, on re-entering the rarer medium, the rays are refracted away from the normal to the surface. The effect in each instance, in our illustration, is a deviation away from the apex of the prism. This, however, is not always the case. The rays may meet the first surface perpendicularly, or they may emerge at the second surface perpendicularly, or they may even be bent towards the apex at one or the other surface. In the last case it must be proved that the refraction towards the apex is less than the opposite refraction at the other surface. The student who is at all familiar with geometry will have no difficulty in satisfying himself that this is so, for he will readily see that the angles of incidence and refraction are greater at that surface at which the refraction is away from the apex than at the other surface. We have already learned that the greater

deviation occurs at the surface where the angle of incidence is greater.

As the incident rays are parallel, the angles of incidence and refraction must be the same for all the rays, and consequently the rays will still be parallel after passing through the prism.

Since the prism deviates light away from the apex, the apparent position of an object as seen through a prism is displaced towards the apex (Fig. 7).

Minimum Deviation.—It was first shown by *Sir Isaac Newton* that the deviation of a ray of light is less when it passes through a prism symmetrically, the angles of incidence and emergence being equal, as in Fig. 7, than in any other position of the ray, and that the deviation increases at a continually increasing rate as the ray departs from this position.

When the prism is of glass whose index is about 1.5 the deviation of the symmetrical ray is very nearly equal to one-half of the refracting angle of the prism, as long as this angle does not exceed eight or ten degrees. For greater angles the deviation is relatively more. The formula expressing the deviation of a ray by a prism is given in the appendix.

Refraction of a Spherical Wave (Divergent Rays) by a Prism.—When light enters a prism diverging from a point

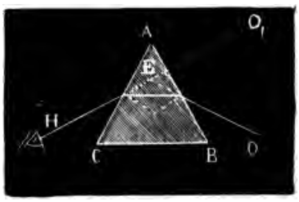


FIG. 7

near the prism the angles of incidence of the various rays will differ one from another, and the study of this condition of refraction is much more complicated than that in which we may regard all the rays as being parallel. We need not, however, enter into a discussion of this subject, for in our use of prisms in ophthalmology we make the assumption that all rays are equally deviated, and we do this without material error. But it

is because of this unequal refraction of the various rays that objects appear distorted when seen through strong prisms, or even through weaker prisms if the rays coming from the objects are far removed from the symmetrical position. Not only is there under such conditions an unequal deviation of the rays from different parts of an object, but also of the differently inclined rays of each pencil, so that the rays which are homocentric before entering the prism will not remain so after passing through the prism. This will be briefly explained when we reach the subject of asymmetrical refraction.

Dispersion of Colors.—We have already learned that prisms have the power of separating light into its various colors. This separation or dispersion of colors is due to the fact that the degree of retardation effected by a dense medium varies with the wave length. The shorter the wave length the greater is the retardation and, consequently, the deviation. As violet is the color of least wave length, the deviation is greatest for this color; while red, being the color of greatest wave length, is the color which undergoes the least deviation in passing through the prism.

In order to obtain a colored spectrum we must exclude all light except a narrow beam, for otherwise the waves which pass through various parts of the prism overlap and form the compound light, and only that part of the light which passes along the borders of the prism is tinged with color. The apex border will be tinged with violet, since this color is deviated farther towards the apex than any other color; so the base border will be tinged with red, since this color undergoes less deviation than any other color.

Numeration of Prisms.—There are several methods of measuring the strength or deviating power of prisms. The method which was formerly used altogether in ophthalmology consists in numbering the prism in terms of its refracting angle (Pr. 1°, 2°, 3°, etc.). The theoretical disadvantages of this method are obvious, since no consideration is given to the refractive index of the material of which the prism is made.

The first improvement in prism notation was made as a result of the discussion of this subject by members of the Ophthalmological Congress held in Washington in 1887. In the method proposed at this Congress the prism is numbered in

terms of the minimum deviating power (Pr. 1^d, 2^d, etc.). We have learned that in weak prisms the minimum deviating power is about one-half of the refracting angle. A prism of 2^d is therefore equivalent to a prism of 4°, as measured by the refracting angle system. A disadvantage of this system of numbering prisms in the degrees of minimum deviation is the liability of its confusion with the first system, since in each case the unit of measure is the degree.

In order to obviate confusion of the deviating power with the refracting angle, and at the same time to introduce the decimal system into prism notation *Dennett* proposed the *centrad system*. In this the minimum deviation is measured in *centrads,* a centrad being $\frac{1}{100}$ of the radius as measured on the circumference. The circumference of a circle being measured by 360°, and the radius being approximately $\frac{1}{6.2832}$ of the circumference, it follows that the centrad ($\frac{1}{100}$ of the radius) is 34′ 22″—slightly more than one-half of a degree.

The method, however, which has gained most favor and which has already come into quite general use in this country is the *prism diopter system.* This system, which was introduced by *Prentice* in 1890, differs from the centrad system chiefly in that the prism diopter is measured on a straight line, while the centrad is an arc of a circumference.

A *prism diopter* is the unit represented by a prism which deviates *the ray of perpendicular incidence* (not the ray of minimum deviation) $\frac{1}{100}$ of a meter (one centimeter) at a distance of one meter. This method affords a very easy way of measuring the strength of a prism, for it is only necessary to count on a metric scale the number of centimeters of displacement which a line undergoes when the prism is placed at a distance of one meter from the scale. If there are 2 *cm* of displacement the strength of the prism is 2 prism diopters; if there are 3 *cm* of displacement the strength is 3 prism diopters, etc. The prism diopter has been adopted by the principal optical manufacturers of America, who make all their prisms in accordance with this system of measurement. The character ($\triangle$) is commonly used to express the term prism diopter.

The following table, whose method of derivation may be found in the appendix, gives the deviating power of various prisms as numbered in terms of the refracting angle and the

prism diopter. In estimating the deviating power of the prisms as measured by the refracting angle the refractive index is regarded as 1.52 and the incident ray is perpendicular to the surface of the prism, as it is in the prism diopter system.

TABLE

Refracting Angle		Deviation	Prism Diopter		Deviation
1°	=	31′ — 12″	1Δ	=	34′ — 22″
3°	=	1° — 33′ — 45″	3Δ	=	1° — 43′
5°	=	2° — 36′ — 2″	5Δ	=	2° — 52′
7°	=	3° — 40′ — 2″	7Δ	=	4°
9°	=	4° — 45′ — 1″	9Δ	=	5° — 9′
11°	=	5° — 52′	11Δ	=	6° — 17′
13°	=	6° — 59′	13Δ	=	7° — 24′
15°	=	8° — 10′	15Δ	=	8° — 32′
20°	=	11° — 19′	20Δ	=	11° — 19′

From the foregoing table we see that for the weaker prisms the prism diopter is slightly stronger than the corresponding number in the refracting angle series, and that the difference between the two diminishes as the strength of the prism increases, so that the deviation produced by a prism of 20° (refracting angle) equals the deviation of a prism of 20Δ. Beyond this number a prism as measured by the refracting angle is of greater deviating power than the corresponding number of the prism diopter system.

The meter angle has also to some extent been used as a prism unit. Its value depends upon the interocular distance, which is a variable quantity, and therefore this unit is not suitable for numbering prisms, although, as we shall hereafter learn, it is very convenient for measuring convergence.

Combination of Prisms.—It is desirable that we should know how to determine the single prism which is equivalent to two specified prisms acting in different directions. We can very easily determine the equivalent prism by diagrammatic construction, as is illustrated in Fig. 8. Let us suppose, for instance, that we have a prism of 3Δ, which deviates light to the right

in the horizontal plane, combined with a prism of 2 △, which deviates the rays vertically upward. Starting at *A* we measure off 3 *cm* to the right in the horizontal direction. This distance *A C* represents the deviating power of the first prism. We next measure off *C D* (2 *cm*) in the vertical direction, which represents the deviating effect of the second prism.

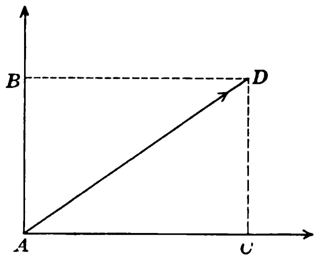


FIG. 8

Therefore, we see that the two prisms acting together deviate a ray from *A* to *D*, and that the deviating action of the single equivalent prism is represented by the line *A D*. We measure this line and find its length is about 3.6 *cm*, and consequently, if the prisms are numbered in prism diopters the equivalent prism will have a strength of 3.6 prism diopters. The direction of the principal plane (the base apex line) of the equivalent prism is also determined by the line *A D*. With the aid of a protractor we find the angle *D A C* to be about 35°, which marks the position of the equivalent prism.

This diagram serves also for reversing the process—for replacing a single prism acting in an intermediate meridian by two prisms, one acting vertically and the other horizontally.

Reflection

That part of the wave of light which, instead of entering the second substance, glances off from the surface and continues to travel in the first substance, is said to be *reflected.*

When a wave of light is incident upon a surface separating two substances the proportion which is reflected depends not only upon the transparency of the second substance and upon its power of absorbing light, but also upon the angle at which the rays meet the surface. The amount of light which enters

a medium diminishes, while the amount which is reflected increases as the obliquity of the rays increases.

It is by reflection that non-luminous objects are visible to us, and it is by means of the unevenness of the surfaces that we are able to see the details of objects. Light reflected in this way from unpolished surfaces is said to be *irregularly* reflected, or *diffused* or *scattered.*

On the other hand, the light which is reflected from polished surfaces is said to be *regularly* reflected. By such reflection we do not see the surface, but a reproduced image of the luminous body from which the light proceeds. The images formed by reflection at the smooth surfaces of the cornea and crystalline lens are of the utmost importance in ophthalmometry, and it is chiefly with a view to the study of these images that we devote our attention here to the phenomena of reflection.

The smoother a surface is the greater is the regular reflection and the less is the diffused light; but even in highly polished surfaces there is usually some irregular reflection by which the surface is rendered visible. At times, however, especially when the illumination is weak, the presence of the reflecting mirror may altogether escape our attention. As is well known, this fact is sometimes made use of in the production of theatrical illusions.

The Law of Reflection.—We have learned that the law of refraction was first discovered experimentally and was afterward proved mathematically as being in conformity with the wave theory of light. The same is to be said of the law of reflection, but this law, being more apparent upon superficial

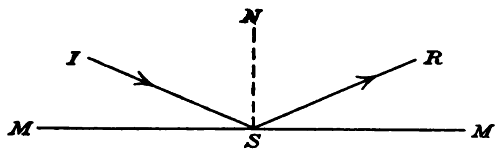


FIG. 9
NSI (angle of incidence) = *NSR* (angle of reflection).

observation than the law of refraction, was discovered at a much earlier date than the latter. The law of reflection was, in fact, known to the ancients. It is usually expressed in the following terms:

The incident and the reflected ray lie in a common plane with the normal to the surface, and the angle of incidence (the angle which the incident ray makes with the normal) is equal to the angle of reflection (the angle which the reflected ray makes with the normal). (Fig. 9.)

Reflection at Plane Surfaces.—When the reflecting surface is plane, as *M M* in Fig. 10, all the normals to the surface are parallel, and since the angles of incidence and reflection are

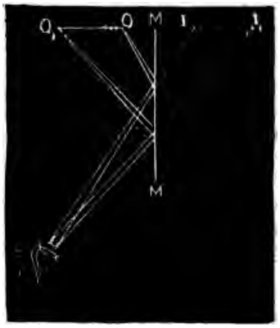


FIG. 10

equal, it follows from the geometrical relations that the point *I*, which is the image of *O*, is as far behind the surface as *O* is in front of it. So also I_1, the image of O_1, lies as far behind the mirror as O_1 lies in front of it.

If $O\ O_1$ represents an object, $I\ I_1$ is the image formed by reflection of this object. The object and its image are of equal size, but there is a lateral reversal of the image relatively to the object, for the point *O* of the object is on the extreme right, while its image *I* is on the extreme left.

Since the rays of light do not actually emanate from the points of the image behind the reflecting surface, but only appear to come from these points, these points constitute a *virtual image* in contradistinction to those images in which the image is actually formed by the meeting of the rays. Images of the latter kind are called *real images.*

Total Reflection.—We have learned that as the obliquity of rays increases the reflected portion of the wave increases at the expense of the portion which enters the second substance.

If the second medium is denser than the first some of the light will always enter this denser medium no matter how great the obliquity of the rays may be; but this is not so when the second medium is the rarer of the two, for when the rays reach a certain degree of obliquity none of the light passes into this rarer medium, the entire wave being reflected.

The reason for this phenomenon of total internal reflection is readily understood from the accompanying illustration (Fig. 11). When the obliquity is such as represented by the ray $O\,S\,R$ the corresponding angle of refraction is ninety degrees,

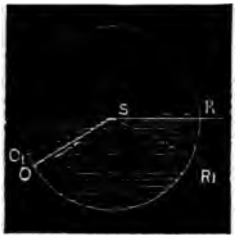


FIG. 11

and a ray $O_1\ S\ R_1$ whose obliquity is greater than that of $O\ S\ R$ would require a still greater angle of refraction, but as the angle of refraction cannot be greater than ninety degrees, we have an impossible condition. No light can pass out of the dense medium under these circumstances.

The angle at which light ceases to pass out of a dense medium (*the critical angle*) can be determined by experiment or from the formula of refraction. By making the angle of refraction (r) equal to ninety degrees in this equation we obtain the corresponding value of the angle of incidence as expressed in terms of the sine of this angle and the refractive index ($\sin i = n$). If we know the refractive index we can ascertain the value of the limiting angle of incidence or the critical angle from a table of sines. On the other hand we may determine the critical angle by experiment and deduce therefrom the refractive index.

The phenomenon of total reflection is of great practical importance in the construction of certain optical instruments, for by its means the direction of rays can be changed with very little loss of light.

It is largely to this phenomenon also that the diamond and other gems owe their brilliancy. Because of the high refractive index the critical angle is small and much of the light which enters the gem undergoes total reflection. After one or more reflections the rays, meeting a surface perpendicularly or nearly so, pass again into the air, and may thus enter the eye of an observer.

The following authorities have been consulted in the preparation of the foregoing chapter:

Des-Cartes, *Dioptrice.*

Newton, *Opticks.*

Gage, *Elements of Physics.*

Ganot, *Physics.*

Heath, *Geometrical Optics.*

Preston, *Theory of Light.*

Jackson, *Designation of Prisms by the Angle of Deviation,* Report of Ninth International Congress, 1887.

Dennett, *Prisms and Prismometry,* Norris and Oliver's *System of Diseases of the Eye.*

Prentice, *A Metric System of Numbering and Measuring Prisms,* Archives of Ophthalmology, 1890.

CHAPTER III

REFRACTION AND REFLECTION AT SPHERICAL SURFACES

We have seen that an image of an object can be projected on a screen by allowing a minute pencil of light to pass through a pinhole opening in an opaque diaphragm, but that owing to the small amount of light that can be allowed to pass through the opening without blurring of the image the illumination of the image is very feeble. Much brighter and better images can be obtained by refraction at suitably curved surfaces. By means of a spherical surface separating two media of different density a considerable portion (pencil) of the rays proceeding from a point may be united in another point or focus after refraction. The means by which this takes place is illustrated in Fig. 12,

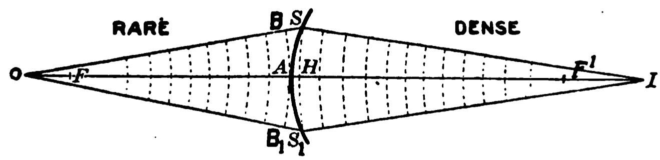


FIG. 12

in which $S\ A\ S_1$ represents a section of a convex spherical surface separating two media, the second medium (that on the right) being denser than the first, while $S\ O\ S_1$ represents a section of a pencil of light proceeding from O* That portion of the wave which travels along $O\,A$ encounters the denser medium sooner than the portions which travel along $O\,B$ and $O\,B_1$. We have learned that the progress of light is less rapid in dense than in rare media; therefore it is evident that while the peripheral rays

*A refracting or reflecting surface is convex or concave according as the convex or concave surface is turned towards the incident rays.

are traveling the distance $B\,S$ (or $B_1\,S_1$) in the rarer medium, the medial ray travels the distance $A\,H$, which is less than $B\,S$ or $B_1\,S_1$. Upon the entrance of the entire pencil into the denser medium we see that $S\,H\,S$ represents the wave front, and that $S\,I$, $O\,I$, and $S_1\,I$, represent rays, all meeting in the focus I. The ray $O\,I$, which is perpendicular to the refracting surface, and which consequently undergoes no deviation, is called the ***optic axis***. The two points O and I are called ***conjugate foci***.

We have in the foregoing illustration assumed without proof that the wave front after refraction, $S\ H\ S_1$, is spherical in form, and that all the rays of the pencil meet in a point. As a matter of fact, the refracted wave front is not mathematically spherical,

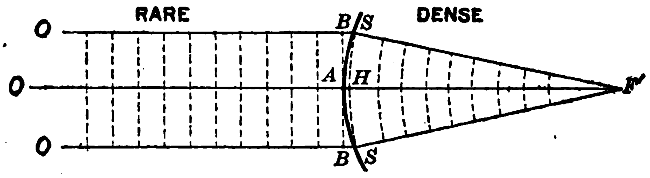


FIG. 13

yet it approximates this form so nearly that in our studies we may base our calculations upon the assumption that (with a certain restriction as to the size of the pencil) all the rays which proceed from a point O can be united in a focus I by refraction at a spherical surface.

The position of the focus I depends upon the following factors: (1) The curvature of the surface, (2) the relative density of the two media and (3) the position of the point O.

When the point O is very far removed from the refracting surface the divergence of the rays is so slight that we may regard them as being practically parallel. When we speak of parallel rays or a plane wave, therefore, we mean either that the rays emanate from a distant point or that they have been rendered parallel by a previous refraction. In either case, that is, whether the rays proceed from a distant point or whether they are actually parallel they are represented diagrammatically as is illustrated in Fig. 13.

Rays which are parallel before refraction at the convex surface $S\,S$ are brought to a focus at F'. This point is called the *posterior principal focus*. When the point of origin of the

rays is at a point *F* (Fig. 14), such that the rays are parallel after refraction, the conjugate focus, *I*, is infinitely distant. The point *F* is called the *anterior principal focus.*

If the point *O* is nearer to the surface than *F* the rays will remain divergent after refraction, but the divergence will be less than it was before refraction, as is shown in Fig. 15. The

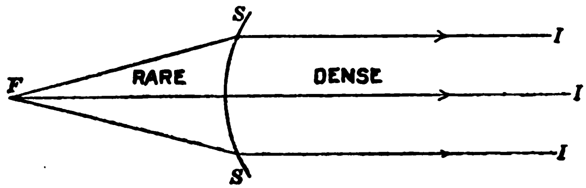


FIG. 14

rays which proceed from *O* will not be united in a real focus, but they will appear to proceed from the virtual focus *I*.

One more condition remains to be considered—that in which the rays of light have been rendered convergent by a previous

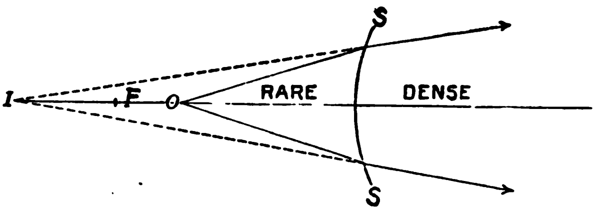


FIG. 15

refraction before entering the denser medium at the convex surface. This condition is illustrated in Fig. 16, in which the rays are converging to the point *O*, and this convergence being increased by the refraction, they are united in the focus *I*.

We must bear in mind in this connection, however, that the refraction is governed by the law that the rays are always bent towards the normal on entering the denser medium. If therefore the rays are so convergent as to be directed towards the center of the surface, all rays meet the surface perpendicularly, and, consequently, there will be no refraction.

If the convergence of the rays is still greater so that they are directed to a point on the optic axis nearer than the center of the surface, the refraction will be opposite to that above described—that is, the convergence will be diminished.

It is apparent that all the foregoing diagrams, illustrating refraction at a convex surface, can be made applicable for illustrating the refraction which occurs when the rays, starting in a denser medium, pass into a rarer medium at a concave surface. In Fig. 12, for instance, rays proceeding from *I* in the dense medium are refracted at the concave surface so as to meet at *O* in the rarer medium. Similarly, by reversing the course of the rays we may apply the other diagrams, and we see that the effect of refraction by a convex surface when the first medium is the rarer, is similar to that by a concave surface when the first medium is the denser.

Summary of Collective Refraction.—Since in all the conditions of refraction thus far illustrated the effect is an

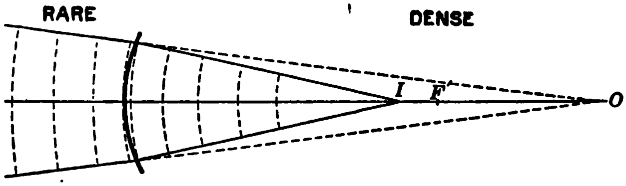


FIG. 16

increase of convergence or a diminution of divergence, or a collecting together of the rays, such refraction is called *collective.*

(1) In collective refraction the two principal foci are real—that is, they are the actual meeting points of rays of light.

(2) Rays proceeding from a point will be brought to a real focus on the opposite side of the refracting surface as long as the point of origin is farther from the surface than is the anterior principal focus (Fig. 12). When the point from which the rays proceed is infinitely distant—that is, when we may regard the rays as being parallel, they meet after refraction at the posterior principal focus (Fig. 13). When the point of origin is so near that there is an appreciable divergence of the rays, the conjugate focus is beyond the posterior principal focus, as in Fig. 12.

(3) Rays proceeding from the anterior principal focus will be parallel after refraction (Fig. 14).

(4) Rays proceeding from a point nearer the refracting surface than the anterior principal focus will remain divergent after

refraction, but the divergence will be less than it was before refraction (Fig. 15).

(5) Rays which are convergent before refraction will have their convergence increased by the refraction (Fig. 16).

Dispersive Refraction.—When rays proceed from a point farther than the center of a concave surface separating two media, the second medium being the denser, the divergence of the rays is increased, as is shown in the accompanying diagram (Fig. 17). The same effect results when the rays pass from a denser to a rarer medium at a convex surface. Such refraction, being op-

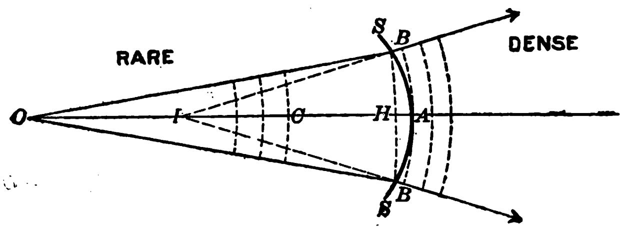


FIG. 17

posite in effect to collective refraction, is called dispersive refraction. It will be more fully explained in the consideration of concave lenses.

Aberration.—Although much larger pencils of light can be utilized in the production of images by refraction than with a simple pinhole opening, there is, nevertheless, a limit to the size of the opening, which may be used in refraction without blurring of the image. The opening must in general be small as compared to the radius of curvature of the separating surface and as compared to the distance of the point of origin of the rays, for the more peripheral rays are refracted too much in proportion to the medial rays of the pencil. This excess of refraction of the peripheral rays gives rise to *spherical aberration.*

The curvature of the cornea of the normal eye is greatest near its center and diminishes towards its periphery. In refraction by a surface of this form less aberration is produced than with a spherical surface.

In some cases of conical cornea the curvature is very great at the apex with a rapid diminution of curvature towards the periphery. In such curvature the great excess of central refrac-

tion causes an aberration which is opposite to that effected by spherical surfaces. This kind of aberration is said to be ***negative***, in contradistinction to ***positive*** or spherical aberration.

There is still another kind of aberration, which is due to the fact, already mentioned, that the various colors do not undergo the same degree of deviation. This is called ***chromatic aberration***.

It can be shown that aberration occurs in refraction by the eye, but not ordinarily to a sufficient extent to interfere with vision. It is chiefly in the construction of microscopes and other delicate optical instruments that aberration is a serious handicap, for the neutralization of which much ingenuity has to be exercised. By the proper combination of lenses and by the use of different kinds of glass (which we owe chiefly to the researches of *Abbe*) a very high degree of efficiency can be attained.

Algebraic Relation between Conjugate Foci.—If we wish to determine the position of the focus conjugate to a specified point we must make use of the algebraic equation which governs the relation between the two foci. I shall show in the appendix the method by which this formula is derived and the different forms in which it may be written. It suffices for our present study to give a brief explanation of the symbols used in the formula in its simplest forms.

It is customary to denote the two principal foci by the letters F and F', F being the anterior and F' the posterior focus, as represented in Fig. 12. It is also customary to denote in the algebraic formula the distances of these two foci from the surface (at its intersection with the optic axis) by the same symbols; that is, F denotes the anterior focal distance and F' the posterior focal distance. The two conjugate focal distances, $A\,O$ and $A\,I$ are denoted by f and f' respectively; the radius of the surface is expressed by r, and the indices of the two media, by n and n_1 respectively. If the surface is convex r is positive (+), and if it is concave r is negative (—).

The anterior focal distance is derived from the equation

$$F = \frac{n\,r}{n_1 - n} \quad (a).$$

The posterior focal distance is derived from the equation

$$F' = \frac{n_1\,r}{n_1 - n} \quad (b).$$

By the proper substitution of these values it is found that the equation which expresses the relation between conjugate points may be written in the form

$$\frac{F}{f} + \frac{F'}{f'} = 1 \quad \text{(c)}.$$

If we denote the distance of the anterior principal focus from the anterior conjugate, $O\,F$, by l, and the corresponding distance, $I\,F'$ (from the posterior principal focus to the posterior conjugate), by l', the foregoing equation can be reduced to the form

$$l\,l' = F\,F' \quad \text{(d)}.$$

This equation is the more convenient when we wish to determine the distance of the conjugate focus from the principal focus, while the first is better when we wish to ascertain the position of the conjugate with reference to the refracting surface.

Formation of Images by Refraction.—The manner in which an object is reproduced in an image is illustrated in Fig. 18, in which A is the refracting surface, C the center of curvature, and the focus I is conjugate to O. It is apparent that I_1 is conjugate to O_1, and I_2 to O_2. The rays emanating from O are therefore focused at I; those from O_1 at I_1, and those from

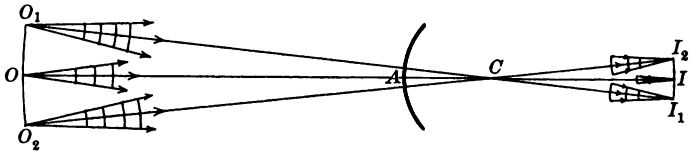


FIG. 18

O_2 at I_2. In the same way every other point of the object $O_1\,O_2$ has its corresponding focus on the line $I_1\,I_2$, and this line is therefore an image or reproduction of $O_1\,O_2$. We see that $O_1\,O_2$ and $I_1\,I_2$ are arcs of circles whose radii are $O\,C$ and $I\,C$ respectively; but since these arcs are very small in comparison with the radii, they differ inappreciably from straight lines. We may therefore, without any material error, say that the image of a straight line $O_1\,O_2$ perpendicular to the *axis* $O\,I$ at O is a straight line $I_1\,I_2$ perpendicular to the axis at I; or, since this is true in all meridians, we say that an object

situated in a plane perpendicular to the axis $O\ I$ has its image in a conjugate plane also perpendicular to this axis.

The axis $O\ I$ is called the *primary axis.* All other axes, as $O_1\ I_1$ and $O_2\ I_2$ are called *secondary axes.*

Relative Size of Object and Image.—It is apparent from the diagram (Fig. 19) that the relative size of the

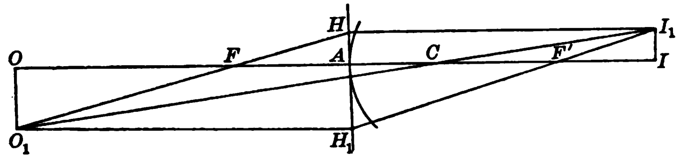


FIG. 19

object and its image is determined by the ratio of the distances $O\ C$ and $I\ C$. This is expressed in an equation as follows:

$$\frac{i \text{ (image)}}{o \text{ (object)}} = \frac{I\ C}{O\ C}.$$

Cardinal Points and Planes.—The cardinal points of a single refracting surface are the two principal foci, the center of curvature, and the point where the surface and primary axis intersect. The center of curvature is called the *optic center* or the *nodal point,* and the point of intersection of the surface and the axis is called the *principal point.* The *cardinal planes* are imaginary planes meeting the axis perpendicularly at the two principal foci and at the principal point.

By means of the cardinal points we can make a diagrammatic construction of the incident and refracted rays, and we can determine therefrom the position and size of the image. The way in which we do this is shown in Fig. 19, in which $O\ O_1$ represents the linear dimension (or one-half of this dimension if the center of the object lies on the optic axis), F *and* F' represent the two principal foci, and $H\ H_1$ the principal plane.

Draw $O_1\ H_1$, representing a ray parallel to the axis $O\ I$; since all rays which are parallel to the axis before refraction must pass through the posterior principal focus after refraction, $H_1\ I_1$, passing through F', represents the course of the refracted ray. Next draw $O_1\ H$, representing a ray passing through F, the anterior principal focus; such a ray must be parallel to the axis after refraction; it will be represented by $H\ I_1$. The point

I_1 where the refracted rays intersect must be conjugate to O_1, and $I\ I_1$, will represent the image of $O\ O_1$.

It will be noticed that the rays have been drawn as if refracted, not at the curved surface, but at the principal plane. The error thus incurred is too slight to be of practical importance, since the focal distances are very great in comparison with the distance between the curved surface and the tangent plane.

The size of the image is determined by the ratio of $O\,C$ to $I\,C$, the relative distance of object and image from the nodal point, as we have already learned; or it may be determined by the ratio of $A\,F$ (the anterior focal distance) to $O\,F$ (the distance of the object from this focus), since $A\,H$ is equal to $I\,I_1$, and the triangles $A\,F\,H$ and $O\,F\,O_1$ are similar.

The relation of the object to the image, as regards their respective linear dimensions, may be expressed by the following double equation:

$$\frac{i\ (\text{image})}{o\ (\text{object})} = \frac{A\ F}{O\ F} = \frac{I\ C}{O\ C}.$$

It is apparent from the foregoing diagrams that real images are inverted relatively to the objects from which they are formed. Virtual images are not inverted.

Spherical Lenses

A lens is defined as a portion of refracting material bounded by one plane and one curved surface or by two curved surfaces. Lenses are divided into two general classes, *symmetrical* and *asymmetrical.* In symmetrical lenses the curvature is spherical, and it is with lenses of this kind that we are now concerned.

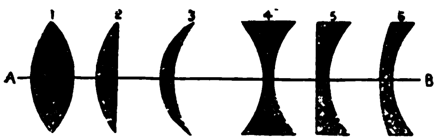


FIG. 20

The various forms in which lenses are made are shown in the accompanying illustration (Fig. 20). They are classified as (1) *bi-convex,* (2) *plano-convex,* (3) *concavo-convex,* (4) *bi-concave,* (5) *plano-concave* and (6) *convexo-concave.* The

lenses comprised in the first group of three are all convex, for the concavity of the third lens of this group is less than the convexity of the other surface. The lenses in the second group of three are all concave.

A concavo-convex, or convexo-concave lens is called a *meniscus* (*moon-shaped* or *crescent*), or in ophthalmology, a *periscopic* lens, because when the concave side is placed towards the eye it affords a more extensive field of view than a plano-convex or double convex lens.

The refractive action of a lens depends, of course, upon its density or refractive index with reference to the medium by which it is surrounded. In our study of lenses it is to be understood that the refractive index of the lens is greater than that of the surrounding medium. The surrounding medium is air in all the lenses which we consider, with the exception of the crystalline lens of the eye.

The straight line which passes through the centers of the surfaces, or which is perpendicular to both surfaces, is the (primary) *axis* of the lens.

The *thickness* of a lens is the distance between the two surfaces as measured on the axis.

In the lenses which are used in the practice of ophthalmology, however, we take no regard of the thickness, for this is so slight as compared with the focal length that its consideration is of no moment.

Convex Lenses.—All convex lenses are collective or convergent in action. In the case of the biconvex lens the rays which diverge from a point are affected collectively first at the convex surface of incidence and then traversing the dense material of the lens they are again refracted collectively in passing from this dense material into the air at the second surface, which is concave to incident rays. Of the total effect produced by the convex lens the part which each surface takes depends upon the relative curvature of the two surfaces and upon the position of the point of origin of the rays. In the plano-convex lens, for instance, rays diverging from a near-point will be refracted collectively at both surfaces, but if the incident rays are parallel the total effect of the lens is produced at the second surface. In the periscopic convex lens the effect of the refraction at the concave surface will, in general, be divergent, but this will

be more than neutralized by the refraction at the convex surface.

What we learned as to the relative position of conjugate foci in refraction at a single spherical surface applies in the main to refraction by convex lenses, as follows:

(1) The two principal foci are real and the two principal focal distances are equal (Fig. 21). In the latter respect lens refraction differs from refraction at a single surface.

(2) Rays proceeding from a point on the axis will be brought

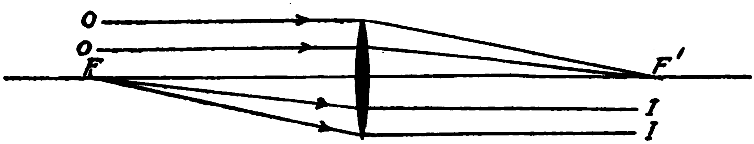


FIG. 21

to a real focus on the opposite side of the lens, as long as the point of origin is farther from the lens than the principal focus (Fig. 22).

(3) Rays which are parallel to the axis before refraction will be brought to a focus at the posterior principal focus, and

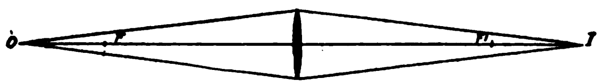


FIG. 22

rays proceeding from the anterior principal focus will be parallel after passing through the lens (Fig. 21).

(4) Rays proceeding from a point on the axis nearer than the principal focus will remain divergent after passing through

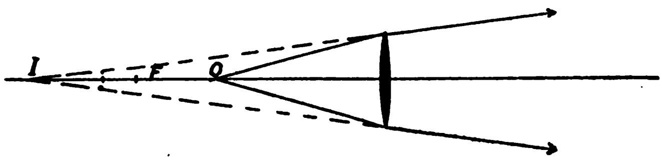


FIG. 23

the lens and will appear to proceed from a virtual focus (Fig. 23).

(5) Rays which are convergent before refraction will have their convergence increased in passing through the lens (Fig. 23 —by reversing the course of the rays).

Formation of Images by Convex Lenses.—A real, inverted image will be formed by a convex lens when the object is farther from the lens than the principal focus (Fig. 24).

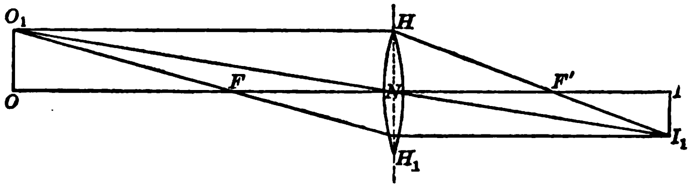


FIG. 24

When the object is at one principal focus no image will be formed, for the rays from any point of the object will be parallel after refraction (Fig. 25).

When the object is so far distant that the rays may be

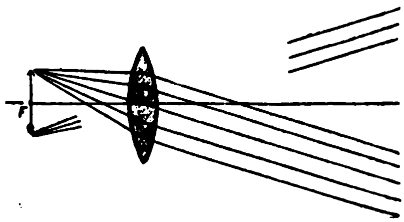


FIG. 25

regarded as parallel, the image will be formed at the posterior principal focus.

When the object is nearer than the principal focus, the image will be on the same side of the lens as the object and it will be virtual.

We see that in the diagrammatic construction of the real image (Fig. 24) the ray $O_1 I_1$ is represented as passing through the lens without deviation. In this respect it corresponds to the nodal ray passing through the center of a single refracting surface. *The center of a (thin) lens is in fact its nodal point, and the oblique rays which pass through this point are secondary axes, since they undergo no deviation.* The reason of this is that for all such rays the lens acts like a plate with parallel faces; the deviation at one surface is neutralized by that at the other (Fig. 26). In thick lenses the nodal rays undergo lateral displacement, but

any such displacement can be neglected in thin lenses. The method of construction of the image is therefore similar to that which we have learned to apply in refraction at a single surface.

Concave Lenses.—In refraction by a biconcave lens rays which diverge from a point beyond the center of curvature of the first surface have their divergence increased at each face of

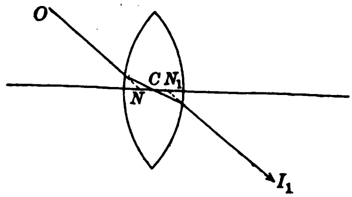


FIG. 26

the lens; while rays which diverge from a point within the center of curvature have their divergence diminished at the first surface, but this diminution is more than overbalanced by the increase of divergence which occurs at the second surface; so also in a plano-concave or a convexo-concave lens the increase of divergence which takes place at the concave surface more than neutralizes

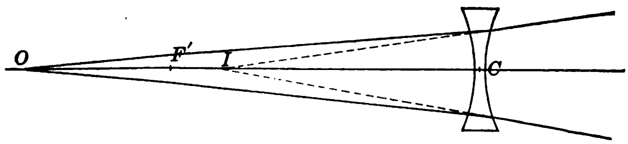


FIG. 27

the diminution of divergence which takes place at the other surface. All concave lenses are therefore divergent or dispersive in action.

(1) We thus see that rays which diverge from a point will never be united in a real focus by a concave lens; they will appear to diverge from a point nearer the lens than the point of origin (Fig. 27).

(2) Rays which are parallel to the axis before entering the lens will be rendered divergent, so that they will appear to have passed through the principal focus (F' Fig. 28).

(3) Rays which are converging to the principal focus (F,

Fig. 28) before entering the lens will be rendered parallel to the axis after passing through the lens.

Cardinal Points of Lenses.—The cardinal points of a thin lens are the *two principal foci* and the *nodal point*. By means of these points the image may be constructed (Fig. 24).

Algebraic Relation between Conjugate Foci in Lens Refraction.—The equation which expresses the relation between conjugate points in lens refraction is determined by applying the equation for refraction at a single spherical surface to the first and then to the second refraction. It is thus found

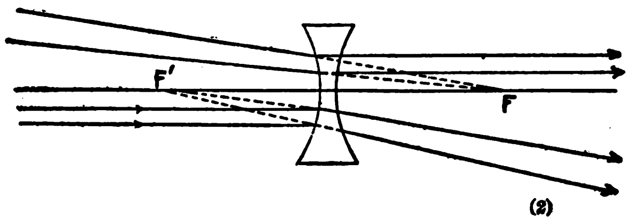


FIG. 28

that in a lens the two principal focal distances are equal and that the algebraic equation between conjugate points becomes

$$\frac{F}{f} + \frac{F}{f'} = 1, \text{ or } l\,l' = F^2.$$

The method of derivation of these equations is given in the appendix.

Numeration of Lenses.—Lenses may be numbered in accordance with their focal length or with their refractive power, the latter being inversely proportional to the former. If F expresses the focal length of a lens $\frac{1}{F}$ expresses its refractive power.

Ophthalmic lenses are usually made of glass of which the index is about 1.52. Upon the assumption that this index is (approximately) 1.5 we can readily prove from the proper algebraic equation that the focal length is twice the radius of curvature ($2r$) if the lens is plano-curved, and that it is equal to the radius (r) if each face of the lens is equally curved. With this understanding therefore the equal curvature $(\frac{1}{r})$ ground on each face of the lens may be taken as the measure of the lens.

In this system, which is the old method of numbering lenses, the inch is the unit of measurement and the unit lens is a lens whose focal length is presumably one inch, because the radius of curvature of each face is one inch.

This system is possessed of a number of disadvantages. In the first place, the inch is not a fixed unit; it varies in different countries. Secondly, owing to the fact that the refractive index is greater than 1.5, the focal length is in reality less than is indicated by the radius of curvature, in accordance with which the lenses are numbered.

These two disadvantages of the inch system are perhaps of minor importance, but there is a third disadvantage which is of a more serious nature. This is that, owing to the comparatively great refractive power of the unit lens, this power must be expressed as a fraction in all those lenses which are commonly used in ophthalmology. Thus a lens whose focal length is twenty inches has a power $\frac{1}{20}$ as great as the unit lens. The power of a 40-inch lens is expressed by $\frac{1}{40}$, and so on. These fractional expressions are very inconvenient in the addition or subtraction of lenses, since the combined action of two thin lenses is equal to the sum of the powers of the lenses.

The disadvantages of the foregoing method are overcome in the metric system of numbering lenses. This system was introduced by *Nagel* in 1866. In it the unit is the meter lens, or lens whose focal length is one meter. The power of this lens is now universally expressed by the word *diopter,* or *dioptry,* which was brought into use by *Monoyer.*

The diopter (1 D) expresses the power of a lens whose focal length is one meter. A lens whose focal length is one-half of a meter is expressed by 2 D, while a lens whose focal length is two meters is expressed by 0.50 D, and so on.

Although this method has entirely replaced the inch system in ophthalmology it is important that one should know how to transform the lens number from one system to the other. This transformation is easily made if we remember that the meter is approximately equal to 40 English inches and that the focal length as expressed in inches will be 40 times as many units as when expressed in terms of the meter. A lens whose focal length is one meter will be measured by the number 40 (a 40-inch lens) in the inch system; the focal length of a lens of 3 D-

will be expressed by $\frac{40}{3}$ in inches, or it will be approximately represented by a 13-inch lens. Conversely, the dioptric number is obtained by dividing 40 by the lens number as expressed in inches. We may express the relation between the two systems in the following equation:

$$\text{Dioptric number} \times \text{inch number} = 40.*$$

Reflection at Spherical Surfaces

Reflection at a convex spherical surface is illustrated in Fig. 29, in which S S represents the reflecting surface and O O_1

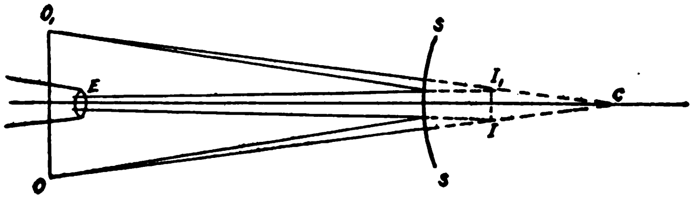


FIG. 29

the object whence the rays of light proceed. From the point O rays diverge, some of which meet the convex surface and are reflected from it in accordance with the law of reflection that the angles of incidence and reflection are equal. Some of these rays may enter an eye or a telescope situated at E. The various reflected rays if prolonged backward would meet at the virtual focus I. In the same way the rays proceeding from O_1 would meet at I_1, and I I_1 is the virtual image of O O_1.

The rays O C and O_1 C, which are directed towards the center of the surface are the nodal rays and the size of the image is determined, as in refraction, by the respective distances of object and image from the nodal point. Thus,

$$\frac{i \text{ (image)}}{o \text{ (object)}} = \frac{I\,C}{O\,C}.$$

When the object is so far distant that the rays may be regarded as parallel, the image is formed at the principal focus of the mirror.† This principal focus lies, as the algebraic equation shows, half way between the surface and its center. As the

* If the Paris inch is used the number 40 should be replaced by 36.

† The two principal foci coincide in position in reflection.

object approaches the mirror the image behind the mirror also approaches the surface. The image is always ***virtual, erect*** and ***smaller than the object.***

Images of this kind are formed by reflection at the surfaces of the cornea and at the anterior surface of the crystalline lens, and it is by means of these images that we determine the radii of curvature of the surfaces.

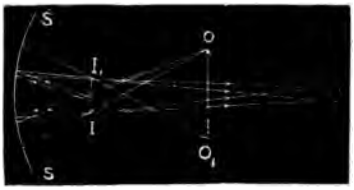


FIG. 30

Reflection at a concave surface is illustrated in Fig. 30, in which S S represents the concave surface and O O_1 the object whence the rays proceed. In this case a real inverted image of the object is formed at I I_1. The size of this image is governed by the same formula as that given above for convex mirrors. As in the convex mirror, the principal focus lies half way between the surface and its center. A real inverted image of this kind is formed by reflection at the posterior surface of the crystalline lens, and by the measurement of this image we determine the radius of curvature of the surface.

Spherical aberration occurs in images by reflection as it does in refraction, but not to an extent great enough to materially affect the result in such measurements as we have to make.

In the convex mirror the principal focus is behind the mirror and it is impossible to place an object at this focus, but in the concave mirror an object may be so placed and the rays reflected by the mirror under this condition will be parallel.

If we place an object at I I_1, the image will be represented by O O_1, for the two conjugate foci are interchangeable.

When the object is nearer the mirror than the principal focus the image will be virtual, erect and larger than the object.

Thus we see that convex mirrors have a divergent effect and concave mirrors a convergent effect upon light rays, which, as we know, is opposite to the action of these surfaces in refraction.

Algebraic Relation between Conjugate Foci in Reflection.—The different conditions of reflection may be verified and the position of conjugate foci determined by the algebraic equation which expresses the relation between these foci.

Any formula for refraction may be converted into the corresponding formula for reflection by imposing the condition that the refractive index is equal to minus one ($n = -1$). This comes by making the angles i (incidence) and r (reflection) equal but of opposite signs.

By making this change in (a) and (b), p. 41, we derive the position of the principal focus of a spherical mirror from the equation

$$F = \frac{r}{2} = -F'.$$

The following authorities have been consulted in the preparation of the foregoing chapter:

Gage, *Elements of Physics.*

Ganot, *Physics.*

Heath, *Geometrical Optics.*

Juler, *Ophthalmic Science and Practice.*

Preston, *Theory of Light.*

Abbe, *Ueber Verbesserung des Mikreskops mit Hilfe neuer Arten Opt. Glasses.*

Nagel, *Die Anomalieen der Ref. und Accom. des Auges,* Graefe-Saemisch Handbuch, 1st ed.

Landolt, *Introduction of the Metrical System into Ophthalmology,* Royal London Ophthal. Hosp. Reports, vol. viii, part iii.

Burnett, *The Meter-Lens, Its English Name and Equivalent,* N. Y. Med. Jour., 1886.

CHAPTER IV

COMPOUND OPTICAL SYSTEMS

A series of spherical surfaces bounding media of different density, all the surfaces being centered on a common axis, constitutes a *compound optical system.* Refraction by a compound system is illustrated in Fig. 31. The point from which the rays diverge is represented by O. The rays diverging from this point are refracted at the first surface A_1 so that they are directed towards I_1, but before reaching I_1 they undergo a second

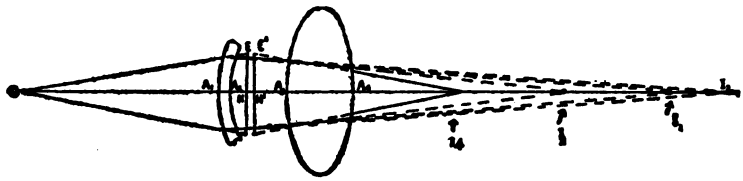


FIG. 31

refraction at the surface A_2. This refraction in our illustration is divergent and the rays are now directed towards I_2, but before reaching this point they are again refracted at A_3, and finally after the fourth refraction at the surface A_4 they are united in a focus at I_4.

It was first demonstrated by *Gauss,* an eminent mathematician of the eighteenth century, that two points which are conjugate in the refraction by a compound system of any number of surfaces are related by the same algebraic formula as in a single refraction. There is this difference, however, that the foci are not measured from a single point (the principal point), but from *two principal points* separated by an interval. The anterior focal distances are measured from the first principal point, while the posterior focal distances are measured from the second principal point.

The principal points are defined as two points which are conjugate in the refraction by the entire system, and which are so situated that a ray directed towards a point in one principal plane will appear after refraction to proceed from a point in the other principal plane, the two points lying on the same side of the axis and equidistant from it. The principal points are represented by H and H', and the principal planes by E H and E' H'.

Cardinal Points of a Compound System.—The cardinal

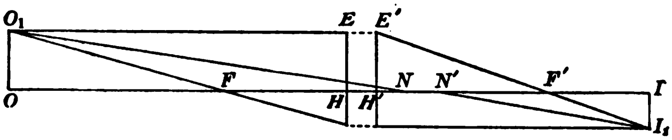


FIG. 32

points of a compound system are *the two principal foci, the two principal points* and *the two nodal points.* The interval between the two nodal points is the same as that between the two principal points. The cardinal points and their planes and the diagrammatic construction of the image are shown in Fig. 32.

The Eye

The eye constitutes a compound system of four surfaces, such as is illustrated in Fig. 31.

Of the four surfaces which constitute this system the first and the most effective is the *anterior surface of the cornea.* This surface is convex to incident light and the index of the corneal tissue is greater than that of the air from which the light comes. The refraction which occurs at this surface is therefore convergent.

The posterior surface of the cornea, at which light passes into the aqueous humor, is the second surface of this system. This surface is also convex. In this case, however, the light is passing from a denser to a rarer medium, for the index of the aqueous humor is less than that of the cornea. The effect of this refraction is, therefore, a partial neutralization of the convergent action of the anterior surface.

The anterior surface of the crystalline lens is the third surface of the system. This surface is convex to the incident rays and the index of the lens is greater than that of the aqueous humor, and therefore this refraction is convergent.

The fourth and last surface is ***the posterior surface of the crystalline lens,*** where the rays enter the vitreous body. This surface is concave to incident rays which are passing from a denser to a rarer medium. The refraction is therefore convergent.

The crystalline lens is not a homogeneous substance. Its refractive index gradually increases from the cortex to the nucleus. We must, therefore, for the purpose of calculation, substitute for the natural lens an ideal body, which has the same refractive effect as the crystalline lens. *Helmholtz* and others have, by very exact measurements, determined the refractive power of the

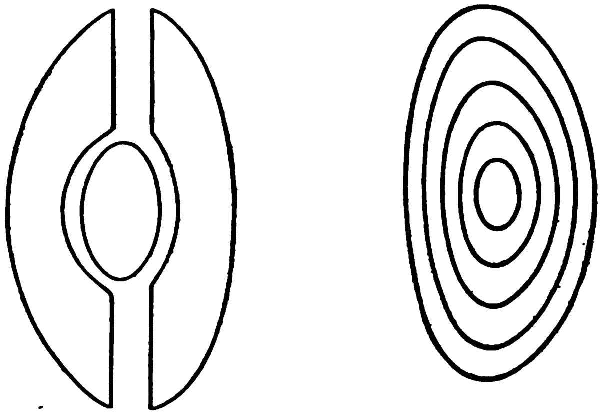


FIG. 33
Illustrating the relative action of the cortical and nuclear portions of the crystalline lens (*Landolt*).

human lens, thereby making it possible for us to substitute for this lens an equivalent lens which has the same curvatures and thickness as the natural lens, but a uniform index.

The equivalent index of the crystalline lens is not, as one might suppose, the average of the indices of the component portions of the lens. It is, on the contrary, higher than the highest index of the natural lens. This is because the curvature of the nucleus is greater than that of the cortex, so that this cortex acts as two divergent menisci would act if applied to the nucleus in such manner as to neutralize a part of the convergent action of the nucleus (Fig. 33). If the index of these two menisci were as high as that of the nucleus, they would neutralize more of the convergent action of the highly curved nucleus than they

do as they are constituted with a lower index, so that if the whole lens had the index of the nuclear portion, its convergent action would be less than it actually is. It is therefore apparent that an effect equal to that of the crystalline lens may be obtained by means of an ideal lens of corresponding curvature and of uniform index only if this index is higher than the index of the nuclear portion of the natural lens.

As we are able to simplify the study of the refractive action of the eye by substituting the equivalent for the natural lens, so we may still further simplify this study by assigning to the corneal tissue the lower index of the aqueous humor. The thickness of the cornea is very slight (1 *mm*) and there is very little difference between the index of the cornea and that of the aqueous.

We may therefore disregard the cornea entirely and assume that the rays enter the aqueous humor directly from the anterior surface of the cornea. The optic system of the eye, with this assumption, consists of three surfaces and three media, and we may consider it as composed of a single refracting surface (the cornea) in combination with a single lens (the crystalline).

Although for ordinary purposes of study we may make this assumption, we find that the mathematical eye deduced under this condition is appreciably shorter than that which results from the consideration of all four surfaces. Therefore, in order to obtain a mathematical result agreeing as closely as possible with the length of the human eye as determined from anatomical examination, I have used all four surfaces in my calculations which are given in the appendix.

Formation of Images by the Eye.—Since the eye constitutes a convergent refractive apparatus, it is apparent that rays of light entering an eye from an external object (situated without the anterior focus of the eye) will be brought to a real focus at some point behind the cornea and that a real inverted image of the object will be formed, as is represented in Fig. 34.

The fact that the image is inverted has led some persons to wonder why we do not see objects in an inverted position. It is only necessary to bear in mind that we do not see the retinal image at all. This image does not enter into the consciousness of vision.

By an innate mental faculty we assume that stimulation

received through certain fibers, which in turn are connected with a certain part of the retina, is produced by an object situated in a certain direction. Since light proceeding from points on the left must (under ordinary conditions) stimulate certain points on the right side of the retina, and *vice versa,* we assign to objects their position in space in accordance with this fact.

The relative direction of any point in space from its image on the retina can only be expressed by the straight line which joins these two points. In a single refraction the nodal ray is a straight line connecting any point of an object with the corresponding point of its image, but when in a compound system the nodal ray undergoes lateral displacement, this ray is not a straight line. In the eye the lateral displacement is practically imperceptible, since the interval between the two nodal points is only .37 *mm.* *We may therefore regard the nodal ray as the line of visual projection* (Fig. 34).

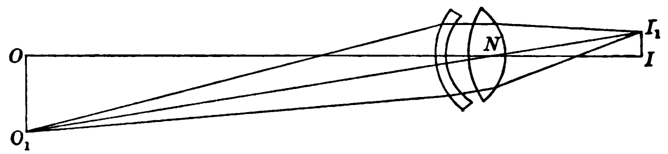


FIG. 34

Relative Size of Object and Image.—We have the same equations for determining this relation as we have in simple systems:

$$\frac{i \text{ (image)}}{o \text{ (object)}} = \frac{I N'}{O N} = \frac{H F}{O F}. \quad \text{(Fig. 32.)}$$

Of these two relations the former—that is, the ratio of the distances of the object and its image, respectively, from the nodal point—is perhaps the more convenient for general use; but when we wish to compare the images of the same object as formed by different refractive systems we find it easier to make use of the second relation. In making the comparison of different systems we see that as long as the distance ($O F$) of the object from the anterior focus is unchanged the linear dimension of the image is proportional to the anterior focal length of the refracting system.

The Visual Angle.—The angle which an object, or its image, subtends at the nodal point of the eye is called the

visual angle. In Fig. 35 the visual angle is represented by *O N O* or *I N I.*

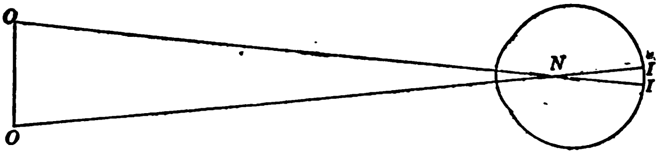


FIG. 35

The Schematic Eye.—The measurements of the average normal eye, as determined by calculation, constitute the *schematic eye.* The average values of the various curvatures, indices and intervals between the surfaces have been determined from measurements made by scientific investigators. A short description of the way in which the results were obtained will be found in a subsequent chapter (The Normal Eye). The values upon which we base our calculations are given in the following table.

RADII OF CURVATURE

Anterior surface of the cornea	7.8 *mm* (r_1)
Posterior surface of the cornea	6 *mm* (r_2)
Anterior surface of the lens	10 *mm* (r_3)
Posterior surface of the lens	6 *mm* (r_4)

	INDICES	THICKNESSES
Cornea	1.377 (n_1)	1 *mm* (t_1)
Aqueous humor	1.337 (n_2)	2.6 *mm* (t_2)
Lens	1.437 (n_3)	4 *mm* (t_3)
Vitreous body	1.337 (n_4)	

By substituting these values in the proper equations and imposing the required conditions, I have obtained the following data for the schematic eye, which is illustrated in Fig. 36.

From summit of cornea to first principal point	1.77 *mm*
From summit of cornea to second principal point	2.14 *mm*
From summit of cornea to first nodal point	7.09 *mm*
From summit of cornea to second nodal point	7.46 *mm*
From summit of cornea to anterior focus	13.99 *mm*
From summit of cornea to posterior focus	23.22 *mm*
Anterior focal distance (measured from first principal point)	15.76 *mm*
Posterior focal distance (measured from second principal point)	21.07 *mm*

The Reduced Eye.—Since the interval between the two nodal points of the eye is only .37 *mm,* we may, for the purpose of studying the eye as a refractive apparatus, neglect this interval without any material error. With this simplification the eye

is comparable to a single surface separating two media whose indices are 1 (the index of air) and 1.337 (the index of the vitreous) respectively.

As far as the size of the image is concerned, there is no difference between the compound system (the schematic eye)

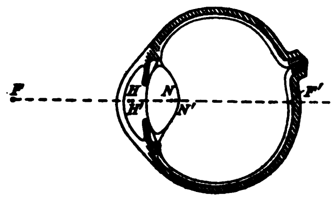


FIG. 36

The schematic or *average* normal eye. The anterior and posterior principal foci are represented by F and F' respectively; the first and second principal points by H and H', and the nodal points by N and N'

and its simple substitute, but as regards the position of the image, we must remember that in the compound system all posterior focal distances are measured from the second principal point, .37 *mm* from the first principal point, and that this dimension must be added to any conjugate focal distance in order that the position of the image may conform to that in the compound system.

Listing's Reduced Eye.—*Listing,* who first reduced the schematic eye to a simple equivalent, placed the imaginary surface between the two principal points and allowed the two principal foci of the schematic eye to retain their positions. In this substitution the focal distances are not strictly identical with those of the schematic eye, although the discrepancy is too slight to be of practical importance. Listing's reduced eye does not, however, accurately represent the normal eye. This is chiefly because he adopted too high a refractive index (1.4545) for the lens, so that his schematic eye, on which the reduction is based, is too short.

Donders's Reduced Eye.—Of the several other equivalents which have been proposed for the schematic eye, only the reduced eye of *Donders* requires mention. In this reduction the anterior focal distance is 15 *mm,* the posterior focal distance is 20 *mm* and the radius of the imaginary surface is 5 *mm.*

These values are taken because with them, as we readily learn from equation (a) the value of n is 1.333, which is the index of water.

While this system does not very closely approximate the schematic eye, it furnishes very convenient data for the construction of an artificial eye for the study of refraction.

The Aphakic Eye.—When the crystalline lens is not present in an eye the eye is said to be aphakic. In this condition, in which the rays of light pass directly from the aqueous to the vitreous without the intervention of the lens, the focal distances of the eye differ materially from those of the normal eye.

Since the aqueous and vitreous have practically the same index, the aphakic eye presents only two surfaces—the anterior and posterior surfaces of the cornea. We have learned that the two corneal refractions may be replaced by a single refraction at the anterior surface of the cornea, which, therefore, constitutes, in our calculations, the total refraction by the aphakic eye.

Focal Distances of the Aphakic Eye.—From the equation

$$F = \frac{r}{n - 1}$$

we find that the anterior focus in the corneal refraction lies 23.14 *mm* in front of the cornea, and from the equation

$$F' = \frac{n\,r}{n - 1}$$

we find that the posterior focus lies 30.94 *mm* behind the anterior surface of the cornea.

Relative Position of the Retina and Posterior Principal Focus of the Eye.—The study of this relation in detail will occupy our attention in subsequent chapters. It suffices to state here just what this relation may be and to define the meaning of the terms used, so that we may be able to understand the various optical problems which present themselves.

When the retina intersects the optic axis of the eye at its posterior principal focus the eye is adapted to receive a clear impression of a distant object. This condition, as it occurs during complete relaxation of the ciliary muscle, is called *emmetropia.* Any deviation from emmetropia is called *ametropia.*

Hyperopia is that form of ametropia in which the retina lies in front of the principal focus during relaxation of the ciliary muscle, or it is that condition in which the eye is relatively too short. In hyperopia the image of a distant object, as formed on

the retina during relaxation of the ciliary muscle, will be blurred and the image of a near object will be even more blurred.

Myopia is that condition in which the retina lies behind the principal focus during relaxation of the ciliary muscle, the eye being relatively too long. In myopia the image of a distant object will be blurred, but the image of a near object may be clearly formed on the retina.

Astigmia (astigmatism) is that condition in which, owing to asymmetry of curvature of one or more of the refracting surfaces, the eye if emmetropic in one meridian will be either hyperopic or myopic in a meridian at right angles to the emmetropic meridian; or the eye may be hyperopic or myopic in both principal meridians, but more so in one than in the other. Or, again, it may be hyperopic in one and myopic in the other meridian.

Accommodation.—In the refraction by the eye the position of the image is not appreciably altered by changing the position of the object as long as this distance is not less than about six meters, or twenty feet. For all objects which are not nearer the eye than this limit we regard the rays as being parallel and the conjugate image as being formed at the principal focus. But when an object is nearer than this its conjugate image falls perceptibly behind the principal focus, and consequently behind the retina if the eye is emmetropic, and more so if the eye is hyperopic.

In order that a near object may be clearly seen, the image must be brought forward so that it will be focused on the retina. This is normally accomplished by an increase in the convexity of the crystalline lens under the influence of the ciliary muscle. This adaptation of the eye for various distances is called *accommodation.*

Since accommodation is effected by a change in the curvature of the lens, the optical system of the eye varies, in near vision, with every variation in the distance of the object. The focal distances are shortened by accommodative action, so that the retina lies behind the principal focus as in the myopic eye.

Presbyopia.—The power of accommodation undergoes a gradual diminution with an increase of age, so that eventually the eye is unable to adjust itself for near objects. When the focusing power has suffered this physiological loss to such a

degree that, after the correction of any existing ametropia, clear vision is impossible at a distance of 22 *cm* (9 inches) the eye is said to be presbyopic *(Donders)*.

The following authorities have been consulted in the preparation of the foregoing chapter:

Heath, *Geometrical Optics.*
Landolt, *Refraction and Accommodation of the Eye.*
Gauss, *Dioptrische Untersuchungen.*
Donders, *Anomalies of Refraction and Accommodation.*
Listing, *Dioptrik des Auges,* Wagner's *Handwörterbuch der Physiologie.*

CHAPTER V

REFRACTION AT ASYMMETRICAL SURFACES

By an asymmetrical surface we mean a surface whose curvature, being regular or symmetrical in any meridian, varies by infinitesimal gradations with a like variation of the meridian.

In spherical surfaces, to which we have hitherto devoted our attention, the curvature is the same in all meridians, and in our study of refraction we have represented this curvature diagrammatically by an arc of a circle, which is the curvature of any section of a sphere. Since in any other meridian the curvature is the same, we know that whatever deductions we reach as to the refractive effect in this meridian will be true for all meridians. But this will evidently not be so in the refraction which takes place at asymmetrical surfaces.

Principal Meridians.—Fortunately we can by the aid of two meridians, those of greatest and of least curvature, the two being at right angles to each other, trace the path of all rays (within the limitations of our algebraic formulæ) which are refracted at an asymmetrical surface. These two meridians are called the *principal meridians.*

The Toric Surface.—We may confine our study of asymmetrical surfaces to those in which the basis of curvature is a circle. In the sphere the circle which is the basal curvature is the same in all meridians. But the torus is generated from two circles of different curvature, lying in the principal meridians, at right angles to each other.

The word *torus*, which is of architectural origin, signifies the ring-shaped base of a column. This form of curvature is shown in Fig. 37 and Fig. 38.

Refraction at a toric surface is illustrated in Fig. 39, in which H H and V V are the principal meridians. We assume that the

horizontal curvature *H H* is greater than the vertical curvature *V V*. First, we examine the rays that enter the second medium

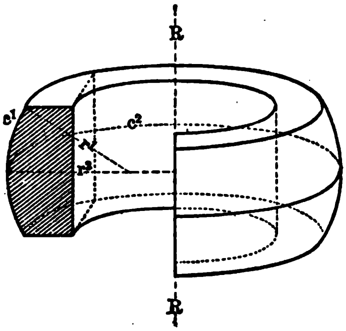


FIG. 37

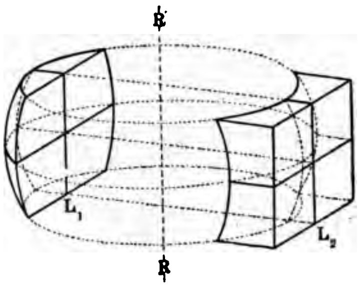


FIG. 38

Toric Curvature (*Prentice*)

in the meridian *H H*. These rays, proceeding from *O*, will be united in a focus at *I*. Next we examine those rays which, proceeding from *O*, enter the second medium in the vertical meridian *V V*. These rays will be united in a focus at *T*.

As regards the refraction of rays which lie in the two principal meridians, therefore, we have no difficulty in understanding what takes place. But when we come to consider those rays which do not lie in these meridians, it is not so easy to form a mental picture of their refracted course. A common error, which is to be found in many text-books of ophthalmology, consists in supposing that as there is a focus for each of the two principal meridians, so there is likewise a focus for each intermediate or oblique meridian; in other words, that there is a series of foci extending between the two foci of the principal meridians.

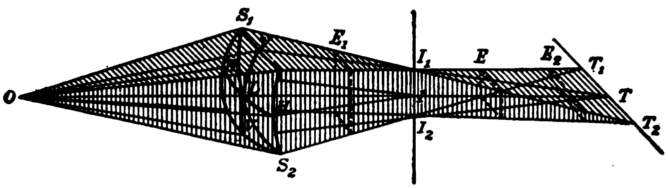


FIG. 39
Refraction at an Asymmetrical Surface

From a careful inspection of the diagram (Fig. 39) we see that all the rays are so governed by the horizontal refraction that they must pass through the vertical line I_1 I_2, erected at the hori-

zontal focus I, and that they are so governed by the vertical refraction that they must pass through the horizontal line T_1 T_2, passing perpendicularly through the vertical focus T. *These two lines are called the focal lines.*

When the point O is so far distant that I and T become principal foci in the two principal meridians, I_1 I_2 and T_1 T_2 are the *principal focal lines,* and I T is the *principal focal interval.* This interval is also called *Sturm's interval,* in honor of the demonstrator of asymmetrical refraction.

The rays O S_1 and O S_2 lie in the oblique meridian S_1 L S_2; the former ray (O S_1) after refraction meets the first focal line at I_1 and the second focal line at T_2; the other ray O S_2 meets the first focal line at I_2 and the second focal line at T_1. It is apparent therefore that these two rays never meet each other after their refraction, and that homocentric rays meeting the asymmetrical surface in a common oblique meridian cannot be united in a focus by this refraction. *There is no focus in any oblique meridian.*

Image of a Point in Asymmetrical Refraction.—Since the rays proceeding from a point will never be united in a focus by asymmetrical refraction, no point of an object can by such refraction be reproduced in a sharply defined image. If the light proceeding from the point O in our diagram should be intercepted by a screen at E_1 the image of the point would be a diffused rectangle of light. If the screen were placed at I the image would be a vertical line. At E the image would be a square and at T it would be a horizontal line.

If the aperture were made circular as in the ordinary diaphragm, the image at I and at T would not be altered, but at E_1 and E_2 the image would be elliptical and at E it would be a circle. The latter is called the *circle of least confusion.*

Image of a Line in Asymmetrical Refraction.—*The image of a vertical line* passing through O will, as projected upon a screen at I, be a distinct line, for each point of the line will have as its image a vertical line, such as I_1 I_2; but if the screen is placed at T, each point of the line will have as its image a short horizontal line, as T_1 T_2, and the aggregation of all these lines will make a broad and indistinct line as the image of the vertical line. At any other point the image of the vertical line will be made of a superposition of ellipses or circles.

The image of a horizontal line passing through O will be the reverse of that of the vertical line; that is, the image will be a broad and indistinct line at I and a distinct line at T.

It thus appears that the image of a line lying in one principal meridian will be distinct at the focus of the other principal meridian, and most indistinct at the focus of the meridian in which it lies.

The image of a line lying in an oblique meridian will be blurred in all positions of the screen.

The Toric Lens.—The toric curvature of a lens may be convex or concave as shown in Fig. 38. The other surface of the lens may be plane or it may have a spherical curvature ground upon it. We thus have in the toric lens a combination of an asymmetrical surface with a surface of symmetry such as we have already studied.

The Cylindrical Lens.—The cylindrical curvature differs from the curvature of a toric surface only in that the former has no curvature in the direction of the axis of the cylinder. It is in fact a torus in which the radius of one of the generating circles is infinite. A cylindrical lens is bounded on one face by a cylindrical curvature and on the other by a plane surface, which is parallel to the axis of the cylinder (Fig. 40). The line V V which

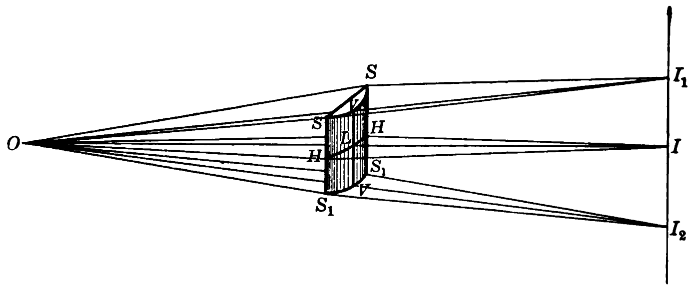


FIG. 40
Refraction by a Cylindrical Lens

passes through the middle of the lens in a direction parallel to the axis of the cylinder, is called the *axis of the lens.*

In the refraction by a cylindrical lens (or *cylinder,* as it is often called) there is no refraction of rays in the direction of the

axis of the lens. This is because in this direction the two faces of the lens are parallel. As this axis represents one principal meridian of the lens, the entire refractive action occurs in the other principal meridian, which is at right angles to the axis of the lens.

Notation of Toric and Cylindrical Lenses.—These lenses are measured in terms of the diopter, which is used for the measurement of spherical lenses. In denoting the strength of a toric lens we express the dioptric strength in the two principal meridians. Thus a convex-toric lens having a refractive power of 6 D in one principal meridian and of 8 D in the other would be designated as + 6 D, + 8 D.

In a cylindrical lens the dioptric marking denotes the refractive power of the lens in its refracting meridian.

Combination of Cylindrical Lenses.—1. *The combination of two cylindrical lenses whose axes are parallel* differs in nowise from the combination of two spherical lenses; the combined lenses are equivalent to a single lens whose refracting power is equal to the sum of the powers of the two lenses.

2. *Two combined cylindrical lenses whose axes are at right angles* are equivalent to a toric lens. If, for instance, the axis of one lens is vertical and that of the other is horizontal, the first lens refracts the rays in the horizontal and the second refracts them in the vertical meridian, just as they are refracted in the two principal meridians of the toric lens.

In a bicylindrical lens one curvature must be ground on each face, so that all the rays, after receiving the refractive effect of the first curvature, may also receive that of the second curvature. If we wish to grind both curvatures upon one surface we must bear in mind that the second curvature must be superposed upon the first without destroying it; we must, *in effect,* bend the axis of the first cylinder into the curvature of the second cylinder, and we see that in so doing we convert the surface into a torus.

If both cylinders have the same curvature the equivalent toric curvature becomes spherical, and the combined effect of *two equal cylindrical lenses* whose axes are at right angles is identical with that of a *spherical lens having the same radius and index.*

Since two unequal cylindrical lenses, combined at right angles to each other, may be regarded as two equal lenses so combined with the addition of another cylindrical lens, it follows

that such a combination is equivalent in effect to a spherical lens combined with a cylindrical lens. Thus the refractive effect is identical whether the two curvatures are ground as a *toric,* a *bicylindrical,* or a *sphero-cylindrical lens.*

3. *Two cylindrical lenses may be combined, having their axes inclined at an oblique angle.* In this case the two axes of the lenses do not indicate the directions of the principal planes or meridians of refraction in the combination; for the second lens, not being at right angles to the first, deviates the rays out of the plane of the axis of the first lens, and *vice versa.* One would, however, naturally suppose that there must be in such a combination a certain meridian in which the effect of the combined refractions is greatest, and at right angles to this another in which the effect is least. It can, in fact, be demonstrated that this is so whatever may be the angle of inclination of the axes; that *any two obliquely inclined cylindrical lenses* in combination are equivalent to two other cylindrical lenses *at right angles,* or to the equivalent of this—a *sphero-cylindrical* or *toric* lens.

Perhaps more convincing to the student than the mathematical demonstration (which is somewhat complicated) is practical experiment with the trial lenses. Selecting any two cylindrical lenses from the case of trial lenses, and placing them together at any angle, we view through the lenses (which are held before the eye) two straight lines at right angles to each other, as the edges of a test-card. These lines will, in general, appear to be twisted out of their proper relations; but by rotating the combined lenses a certain position can always be found in which the two lines appear (as they are in reality) at right angles to each other. In this case the two lines viewed mark the directions of the principal meridians, and the combination is equivalent to a certain toric, or sphero-cylindrical, or bicylindrical lens having these principal meridians. The nearest equivalent to this combination which is to be found in the trial case may be ascertained by neutralization—a process which will be subsequently described.

Asymmetry of Oblique Refraction.—We have so far confined our attention to direct refraction, in which the axis or medial ray of the pencil of light meets the refracting surfaces perpendicularly. Strictly speaking, there can be only one point of an object from which a direct pencil can pass through a lens

or system of refracting surfaces. This point is the point of intersection of the optic axis and the object. All other parts of the object give rise to indirect or oblique pencils; but when the object is small as compared with its distance from the refracting system, and so situated that its central point lies on the optic axis, the refractive effect differs so little from that of direct pencils that we take no account of the difference.

In the refraction by the eye the obliquity of pencils may be disregarded, because images falling upon the retina at a considerable distance from the optic axis, do not excite in the mind a distinct visual impression. It is only with such pencils as may be regarded as direct that distinct vision is concerned. But in vision which is accomplished with the aid of a lens, the rays which enter the eye are previously obliquely refracted by the lens if this is placed in a tilted position before the eye.

The effect of the oblique position of the lens is that which results from spherical aberration. We know that refraction at a spherical surface increases with the obliquity with which the rays meet the surface. We see, therefore, that if we intercept all but a small pencil of the most oblique rays, these rays will undergo greater refraction than the central rays would have undergone if they had not been intercepted, and that if there is any focus for these oblique rays, it must lie nearer the surface than the focus for the central rays, that is, the refractive action is more powerful for the oblique than for the direct rays.

The mathematical demonstration of what actually takes place in oblique refraction is complicated, but by examining a lens tilted, as in the vertical meridian, we can form a general idea of the way in which the increase of refraction occurs. It is easy to see that in the meridian in which the lens is tilted the refractive effect must be increased by the tilting, but it requires closer attention to see that the effect is also increased, though to a less extent, in the meridian at right angles to the tilting.

There is, therefore, no sharp focus for rays which are refracted with considerable obliquity, but if we take into consideration only small oblique pencils, we may assume that there is a focus of greatest refraction in the meridian of tilting and another focus of least refraction in the meridian at right angles to this; or, in other words, we may for our purposes, say that oblique refraction is similar to refraction at an asymmetrical surface.

In a cylindrical lens the refracting power in the direction of the axis is zero, and it must remain so when the lens is tilted. Tilting a cylindrical lens, therefore, increases its power in its refracting meridian; more so when the tilting is in this meridian.

The asymmetrical effect of tilting lenses has an important bearing in the combination of weak cylindrical with strong spherical lenses. A slight amount of tilting, as is almost unavoidable in near work, may either entirely neutralize the cylindrical effect or increase it beyond what is desired.

The following table (*Green*) shows the rate of increase of a lens when it is tilted in the vertical meridian:

Degrees.	*Vertical.*	*Horizontal.*
0	1.000	1.000
5	1.010	1.002
10	1.042	1.010
15	1.097	1.023
20	1.179	1.041
25	1.297	1.166
45	2.464	1.232

If we wish to find the asymmetrical effect produced by tilting a lens of 4 D, for instance, fifteen degrees in the vertical meridian, we multiply 1.097 and 1.023 respectively by 4. This gives us 4.388 D as the refractive effect of the tilted lens in the vertical meridian, and 4.092 D in the horizontal meridian. The difference .296 D, represents the asymmetry or the strength of the cylindrical lens which would be required to equalize the two meridians.

Asymmetry of Prismatic Refraction.—We have learned that in the passage of light through a prism there is no deviation of rays in the direction of the base-apex line (or axis) of the prism, the two faces of the prism being parallel as regards this direction; but that in the principal plane of the prism the rays are all deflected towards the base of the prism. If all the rays undergo the same degree of deflection, the relative direction (the divergence) of the rays will be unaffected. This is the condition which exists for parallel rays and approximately for very small pencils passing through the prism near the symmetrical ray; but other pencils have their relative divergence altered, for the pencils are altered in length in the principal plane of the prism while they are not affected in the direction of the axis of the prism. This is because the rays which are most removed from

the symmetrical ray are more deflected than the rays which are near this position.

Since this change of divergence takes place in the principal plane of the prism but not in the direction at right angles to this plane, the rays which diverge from a point will lose their homocentric character, and the refraction is comparable to that effected by an asymmetrical surface.

The study of refraction by prisms becomes still more complicated when the rays do not lie in or near the principal plane, as we have assumed, for rays which meet the principal plane obliquely undergo greater deviation than those which lie in this plane.

But, as has been stated in a previous chapter, we assume in ophthalmology that the rays are all equally deviated, and that pencils which are homocentric before entering the prism remain so after passing through it. It is therefore only necessary that the student should be familiar with the fact that this assumption is true in a limited sense, so that he may be able to understand the distorting effect which results from prismatic refraction under certain conditions.

The following authorities have been consulted in the preparation of the foregoing chapter:

Heath, *Geometrical Optics.*

Prentice, *Ophthalmic Lenses.*

Sturm, *Sur la Théorie de la Vision,* C. R. de l'Acad. de Sci. de Paris, 1845.

Green, *Effect of Tilting Lenses,* Trans. Am. Ophthal. Soc., 1890.

Burnett, *Treatise on Astigmatism.*

CHAPTER VI

CORRECTION OF OPTICAL DEFECTS OF THE EYE BY LENSES

Spherical lenses have been used for the improvement of vision for a very long time, and the art of lens making, in a crude way, dates back to the days of the ancients. What is probably the oldest lens in existence is a convex lens of crystal which was discovered in the ruins of Nineveh, and is now in the British Museum (*Borsch*).

The use of lenses worn as spectacles, supported on the face by frames, dates from the latter part of the thirteenth century.

Asymmetrical lenses were introduced by *Airy* in the early part of the nineteenth century, but it was not until after the middle of that century that they came into general use with the great advance made in the study of the refraction of the eye by *Donders* and his collaborators.*

Use of Spherical Lenses

In order that rays of light may be focused on the retina of a *hyperopic eye* without accommodation these rays must be con-

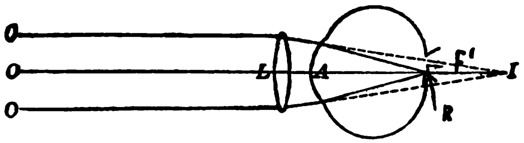


FIG. 41

vergent when they enter the eye. Thus if I (Fig. 41) is conjugate to R on the retina, rays which are converging to I will be so refracted by the eye as to be focused on the retina.

*It has been stated that priority in the use of the cylindrical lens belongs to McAllister, an optician of Philadelphia, in that he corrected a case of astigmia with such a lens in the year 1825. But although the published description of Airy's case bears the date of 1827, he presented this description to the Cambridge Philosophical Society in the early part of 1825.

But rays proceeding from any point of an object are never convergent—they are divergent, or if the point is remote they may be regarded as parallel. We must therefore for the correction of hyperopia render convergent these divergent or parallel rays before they enter the eye. We do this by means of a convex spherical lens placed before the eye. The parallel rays proceeding from a distant point would be focused by the hyperopic eye at F' behind the eye, but before reaching the eye they are refracted by the lens L. Being thereby rendered convergent, they would be focused at I, but before reaching I they are refracted by the eye and are focused at R on the retina.

Since the point I is the focusing point for parallel rays in the refraction by the lens, $I\ L$ is the focal length of the lens which corrects the hyperopia.

The lens which corrects the eye for parallel rays places the eye in the same status as the emmetropic eye for focusing divergent rays; that is, this eye can then focus divergent rays on the retina by the aid of accommodation. If the latter is unavailable or insufficient, a stronger lens must be used for near work.

In emmetropia or corrected ametropia parallel rays can be focused on the retina, but if the crystalline lens is unable to undergo an increase of convexity for the focusing of divergent rays from a near point, a convex lens must be used for near vision. By means of the convex lens divergent rays are made parallel so that they can be focused on the retina. This use of the convex lens is illustrated in Fig. 42. Since O is the

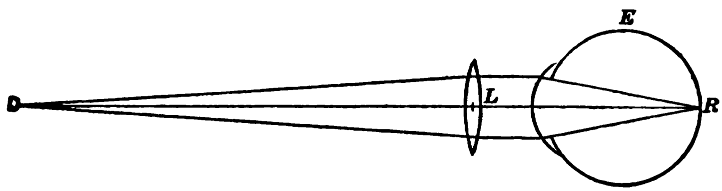


FIG. 42

principal focus of the lens L, we may take the focal length $O\ L$ as the measure of the accommodation required to adapt the eye for an object at the distance of O from the eye. If for instance O is 25 *cm* from the lens, this being placed at a standard position, $\frac{1}{O\ L}$ gives 4 D as the accommodation required.

When some accommodative power remains, but an insufficient amount for near work, a weaker convex lens is used, such as overcomes only a part of the divergence of the rays.

In the myopic eye (Fig. 43) parallel rays from a distant point would be focused at F', in front of the retina, but before entering the eye they encounter the concave lens, L, and are so

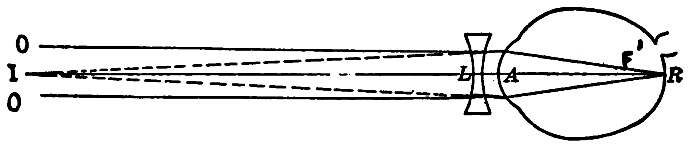


FIG. 43

refracted that they now appear to diverge from I, which is conjugate to R in the refraction by the eye. Therefore a concave lens whose focal length is $I\ L$ will correct the myopia.

Far Point of the Eye.—The point I, which is conjugate to R on the retina, is called the *far point* (*punctum remotum, p. r.*) because it is the farthest point of distinct vision; the image of any more distant point will lie in front of the retina. In hyperopia the far point lies behind the eye, that is, the far point is *negative.*

Effect of Changing the Position of the Correcting Lens.—When a convex lens is placed before the eye in order to cause the image of an object (O, Fig. 41*) to fall upon the retina, O and I are conjugate points in the refraction by the lens. These two points are fixed, but the lens may have any position between A and O. It may be proved, both experimentally and mathematically, that for any lens the line $O\ I$ between conjugate points is shorter when the lens occupies a midway position between these points than in any other position. Conversely, for the fixed points O and I a weaker lens will suffice when this is placed midway between O and I than in any other position.

When the lens occupies this midway position the two conjugate focal distances $O\ L$ and $I\ L$ are each equal to twice the focal length of the lens. Hence, it is apparent that increasing the distance between the eye and the lens increases the correcting power of a convex lens as long as the distance of the lens from the object is more than twice the focal length of the

*The conjugate point O in this diagram is supposed to be so remote that its position on the axis cannot be represented.

lens, and that when this distance is less than twice the focal length of the lens, increasing the distance between the eye and lens diminishes the correcting power of the latter.

In the adaptation of the hyperopic eye for distant vision the distance of the lens from the object is more than twice the focal length of the lens; consequently, a lens which corrects the hyperopia in one position will be too strong or too weak according as it is moved away from or towards the eye; but when the object is near the lens, as in the use of reading glasses, the distance between the object and the lens is usually less than twice the focal length, and a change in position of the lens has the opposite effect—that is, a stronger lens will be required when the distance of the lens from the eye is increased.

Since this is true, we are confronted with the question as to the reason for the common belief that presbyopes whose glasses are too weak acquire the habit of moving them off to the tip of the nose in order to see more distinctly. If this device does render vision better it is probably because of the attendant obliquity of the lenses, whereby the refractive power is increased, but with the disadvantage of an induced asymmetry of action.

In the concave lens, the focal distance being negative, the distance between the object and lens is (algebraically) always less than twice the focal length; consequently, a stronger concave lens is always required when the distance of the lens from the eye is increased. This is apparent from inspection of Fig. 43.

Measurement of Ametropia by the Correcting Lens.— The degree of ametropia may be conveniently measured by the lens required to focus the image of a distant object upon the retina; but since the strength of this lens varies with its distance from the eye, it is necessary to adopt a standard position at which the measuring lens is to be placed. For this purpose it is customary to regard the lens as placed at a distance of 15 *mm* from the eye. This is approximately at the anterior focus.

Effect of Lenses upon the Size of Retinal Images.— In general, a lens placed before the eye alters the size of the retinal image; but spectacle-lenses, owing to the fact that they are worn very near the anterior focus of the eye, usually produce only a slight modification in this respect.

The effect of placing a convex lens at the anterior focus of the eye is illustrated in Fig. 44, in which *A* represents the re-

fracting surface of the reduced eye. We have learned that, in estimating the size of images, the interval between the principal

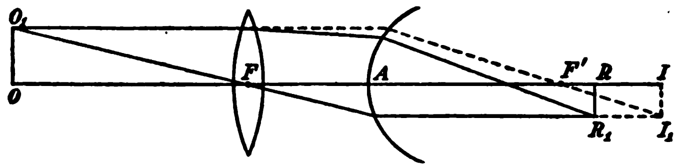


FIG. 44

points may be disregarded; hence, if $A\ F$ and $A\ F'$ represent the anterior and posterior focal distances of the eye, $I\ I_1$ will represent the image of the object $O\ O_1$ in the refraction by the eye alone. If the image $I\ I_1$ lies behind the retina $R\ R_1$, it may be brought forward by a convex lens. When this lens is placed at the anterior focus, as illustrated in Fig. 44, the ray $O_1\ F$, passing through the anterior focus, passes also through the nodal point of the lens; consequently, its direction is unaltered by the lens, and the image $R\ R_1$ on the retina has the same size as $I\ I_1$, formed by the eye without the aid of the lens.

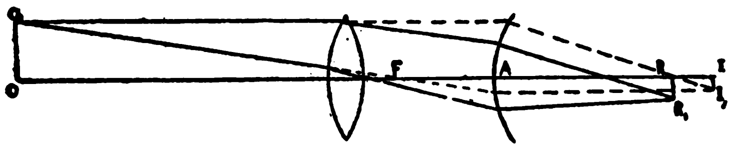


FIG. 45

When the convex lens is without the anterior focus, the image is not only brought forward, but it is at the same time enlarged, as is shown in Fig. 45.

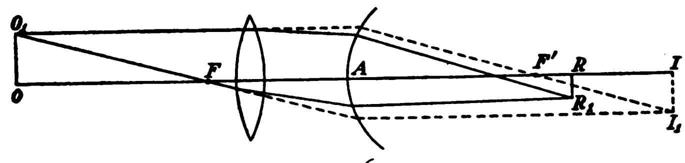


FIG. 46

When the convex lens is within the anterior focus of the eye the image is brought forward, but it is diminished in size, as is shown in Fig. 46*.

*These diagrams, illustrative of special conditions, do not afford a general demonstration; but it can be proved algebraically that for all relations of conjugate foci images are affected in the same way as in these illustrations.

The effect of a concave lens is opposite to that of a convex lens. A concave lens at the anterior focus of the eye moves the image backward without changing its size. When the lens is without the anterior focus the image is made smaller, and when the lens is within the focus the image is enlarged.

We see, therefore, that we cannot properly illustrate the effect of lenses used in the correction of ametropia by means of the enlargement of the virtual image of the convex lens, or by the minification of the virtual image of the concave lens. An actual enlargement or diminution in size occurs according as the lens in combination with the eye produces a larger or smaller image than does the eye alone.

When a convex lens is used as a "magnifying glass" the conditions are somewhat different and further explanation is required. The action of a lens used as a magnifier or simple microscope is shown in Fig. 47. Although the lens may be at or near the anterior focus

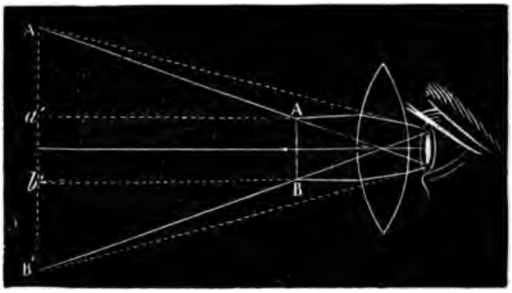


FIG. 47

of the eye, the object *A B* will be seen with magnification. This is because the lens enables us to focus on the retina the rays from the object when this is placed very near the eye. If we could focus rays coming from the object situated equally near the eye without the aid of the lens we would see it with as much enlargement as we do with the lens. But it is only with the lens that rays from so near an object are focused on the retina, and as we are not accustomed to seeing clearly objects placed so near the eye, we unconsciously regard an object so seen as being at a greater distance and as having a proportionately greater size.

In the use of a convex lens for this purpose the object to be magnified is placed at or near the principal focus of the lens. When the observer's eye is emmetropic and he uses no accommodation the object is at the principal focus so that the rays from the object will be parallel when they enter his eye. If he is hyperopic, he will need to have the rays rendered slightly convergent so that he can focus them without accommodation, and the object must be without the principal focus. On the other hand, if he is myopic, the object must be within the principal focus so that the rays will enter his eye in divergent pencils.

We have learned that the position of greatest efficiency of a convex lens is midway between the two conjugate foci and that moving it away from the eye and towards the object diminishes its power when by so moving it we carry it farther from the midway position. The same is true of the magnifying power of a convex lens used in combination with the eye, and any further movement of the lens towards the object diminishes the magnifying power. Practically we must, however, continue to move the lens towards the object until the image on the retina becomes clear which (as has just been shown) is when the object is near the principal focus of the lens. This is the position of greatest magnifying power and any further movement of the lens towards the object diminishes the magnification.

In hyperopia distinctness of vision is attained by accommodative action, whereby the focal distances of the eye are shortened and images are reduced in size. By the substitution of a convex lens placed at the anterior focus the accommodation is relaxed, the focal distances resume their normal dimensions, and images are proportionately enlarged.

When the lens is worn without the anterior focus, there is additional enlargement due to the magnifying power of the lens. Even in high hyperopia, however, the difference in size of images without lens-correction and with it is not great. The difference is, nevertheless, appreciable, for it is possible to discern very slight changes in the dimensions of the stimulated retinal area.

Similarly, when convex lenses are used as reading glasses, these being necessitated by failure of accommodation, retinal images are slightly larger than when the focal distances are shortened by accommodative action.

In myopia distinct distant vision is impossible without a correcting lens. When the myopia is due to axial elongation (the focal distances being normal), the proper concave lens placed at the anterior focus of the eye brings the image to a focus on the retina without changing its size, that is, the image has the same size as it would have in emmetropia. If the correcting lens is worn without the anterior focus of the eye, the image is smaller than in emmetropia.

Enlargement of Images Effected by Removal of the Crystalline Lens.—In aphakia the anterior focal distance is greater than that of the schematic eye in the proportion of about 23 to 16. Since images are proportional to the anterior focal distance, they must be larger after removal of the lens than they are in the normal eye. However, if the axial length of the eye is normal, images as formed by the aphakic eye will lie far

behind the retina, and distinct vision can be obtained only with the aid of a strong convex lens. This lens, if worn as an eye-glass, will be within the anterior focus of the eye in its aphakic condition, and consequently it will reduce the size of images, so that they will more nearly correspond to those of the normal eye.

It is in extreme axial elongation (high myopia) that the enlargement of images resulting from removal of the lens is most noticeable. If the elongation is so great that the posterior principal focus falls on the retina of the eye after its lens has been removed, the image of a distant object will be clearly formed on the retina without any correcting lens. Each linear dimension of the object as thus formed will be about one and one-half times as large as with the concave correcting lens which was required before removal of the lens.

Length of Axis in Ametropia.—If we may assume without error in any case of hyperopia or myopia that the curvatures, indices, and intervals between the surfaces do not differ materially from those of the schematic eye, the degree of ametropia, as measured by the correcting lens, affords a means of estimating the deficiency in length of the eye in hyperopia or the excess of length in myopia.

For this purpose we use the equation

$$l' = \frac{F F'}{l},$$

in which l is the distance of the far point (I, Fig. 41) from the anterior focus, and l' is the distance of the retina from the posterior focus.

In the application of this formula to myopia of 10 D, as measured by the correcting lens placed at the anterior focus, $l = 100$ *mm*. By substituting for F (15.76) and for F' (21.07) their values, we derive 3.3 *mm*, as the corresponding value of l'. Since this is the distance of the retina behind the principal focus, it is the excess of axial length for 10 D of myopia.

In hyperopia of 10 D, as measured by the correcting lens placed at the anterior focus of the eye, l, being negative is -100 *mm* and by the substitution of this value we find that l' is equal to -3.3 *mm*, which shows that in 10 D of hyperopia the deficiency in axial length is 3.3. *mm*.

The deficiency in length of the hyperopic eye is equal to the excess in the same degree of myopia, when these conditions are measured by the correcting lens placed at the anterior focus of the eye.

Each millimeter of deficiency or excess of length corresponds to three diopters of ametropia.

Axial Length of the Eye in Relation to the Probable Refractive Condition after Removal of the Lens.—We may make use of the same equation ($l\ l' = F\ F'$) to determine the probable refractive condition after removal of the lens from the eye.

In the application of this formula to an eye which is emmetropic before removal of the lens, and in which therefore the axial length is presumably about 23.22 *mm*, $I\ F$ ($I\ F = I\ L$, Fig. 41) is denoted by l, and $R\ F'$ is denoted by $-\ l'$. The minus sign is used because R lies on the left of F'. In this equation F and F' represent respectively the anterior focal distance ($A\ F$) and the posterior focal distance ($A\ F'$) of the aphakic eye. The first of these distances is 23.14 *mm*, and the second is 30.94 *mm* (average measurements). We observe also that $R\ F'$ is equal to the difference between $A\ F'$ (30.94 *mm*) and $A\ R$ (23.22 *mm*), or $R\ F' = l' = -\ 7.72$ *mm*.

By substitution of the values of F and F' we have the equation,

$$-\ 7.72\ l = 30.94 \times 23.14$$

From this we find $l = -\ 93$ *mm*.

This means that 93 *mm* is the focal length of the lens which is required to correct the hyperopia after removal of the lens, if the correcting lens is placed at the anterior focus of the aphakic eye; but this focus is about 23 *mm* from the cornea, a greater distance than that at which correcting lenses are worn. We therefore subtract 8 *mm*, in order to reduce the distance to the standard which we have assigned as the position of correcting lenses, and this gives 85 *mm* as the focal length of the correcting lens.

A focal length of 85 *mm* corresponds to a dioptric power of 11.7 D, which, therefore, is theoretically the degree of hyperopia to be overcome after removal of the crystalline lens from an emmetropic eye.

Since individual eyes differ more or less from the schematic eye in their measurements, we must not suppose that the lens as practically determined will correspond exactly with that here derived by calculation. As a matter of fact the lens so derived seems to be slightly stronger than is usually required after removal of the crystalline lens from an eye which was known to have been emmetropic before the formation of cataract. As a rule a lens of 10 D or at most 11 D suffices to correct the hyperopia of such an eye.

In other refractive conditions the same method may be used to determine the probable strength of the lens which will be required to correct the ametropia after removal of the crystalline lens. The only difference between this and the foregoing procedure is that instead of the distance $A\ R$ being equal to 23.22 *mm*, the length of the emmetropic eye, its value must be assigned in accordance with the degree of ametropia.

A condition of practical interest is that in which the eyeball has undergone great elongation with a resulting high degree of myopia. We may then wish to know whether such an eye will be myopic, emmetropic, or hyperopic after removal of the lens.

The posterior focus of the aphakic eye of normal curvature and index, lies, as we have already learned, about 31 *mm* behind the anterior surface of the cornea. If, therefore, the myopic eye is so elongated that the retina is also situated at this distance from the cornea, the eye will be adapted to focus the image of a distant object upon the retina after removal of the crystalline lens.

If under the same conditions the axial length is more than 31 *mm* the eye will still be myopic after it has been rendered aphakic; but if the axial length is less than 31 *mm*, the aphakic eye will be hyperopic.

An axial length of 31 *mm* corresponds to myopia of about 23 D, as measured by the correcting lens at the anterior focus of the eye, and this is therefore the degree of axial myopia which must exist under average conditions in order that the eye may be emmetropic after removal of its crystalline lens. Practically it has been found by those who have removed the crystalline lens for the improvement of vision in high myopia that emmetropia (or a condition approximating this) may result in myopia of various degrees, between eighteen and twenty-five diopters.

Correction of Astigmia

There are two kinds of astigmia: *regular* and *irregular*. The former is due to asymmetrical curvature of the cornea or crystalline lens. The latter arises from irregularity or unevenness of surface, or from heterogeneity of structure. Our attention is here confined to regular astigmia, which is always signified by the term astigmia unless it is otherwise stated.

By referring to our diagram of asymmetrical refraction (Fig. 39) we see that if we place a cylindrical lens in front of the surface so that it increases the refraction of the rays in the vertical meridian to such an extent as to change the vertical focus from T to I, all the rays from O must then meet in the point I; the pencil is again homocentric, and the asymmetry is overcome.

So also if we make use of a concave cylinder so placed as to change the horizontal focus from I to T the rays will meet in the point T. In this case as well as in the former the astigmia is overcome.

Astigmia is therefore corrected by any lens that will equalize the refraction of the eye in the two principal meridians. If the retina were at the focus I, we should use the convex lens with its axis horizontal, while if the retina were at T we should use the concave cylinder with vertical axis. But when, as is often the case, the retina coincides with neither focus, we must add a spherical lens to the astigmia correction so as to bring the rays which are rendered homocentric by the cylinder to a proper focus on the retina.

Distortion of Images in Astigmia.—In investigating the form of images in astigmia we must consider both the blurred image as formed without the correcting lens and the focused image as formed with the aid of the lens.

Since the linear dimensions of the image are proportional to the anterior focal distance of the eye (p. 58), and since this distance is greater as the curvature is less, it is clear that the image as formed in the meridian of greatest refraction is less than that formed in the meridian of least refraction. The retina cannot, however, be in position to receive the focused image in both meridians so that the light is diffused on the retina in the unfocused meridian. The effect of diffusion upon the apparent

size of the image varies with the size of the pupil, and with the relation of the diffusion to the magnification or minification of the focused image. Generally the diffusion on the retina makes the image appear too large in the unfocused meridian whether this is hyperopic or myopic.

When the astigmia is corrected by a lens at the anterior focus of the faulty meridian, the image may be focused on the retina; but the size of the image will remain the same as it would be as formed at its focus without the lens. In other words the corrected image is proportionally too large in the meridian of least refraction or too small in that of greatest refraction. If the correcting lens is worn without the anterior focus the distortion may be further increased by the magnifying or minifying power of the lens.

Owing to the disproportion of the image in astigmia, all lines which are not parallel or perpendicular to the principal

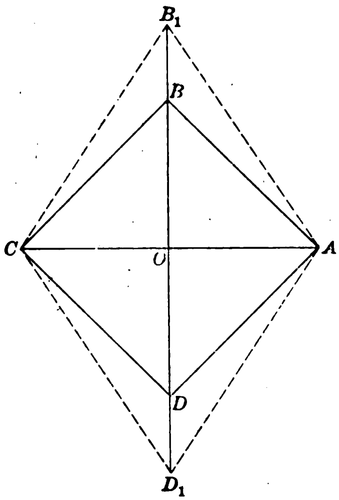


FIG. 48

meridians undergo an angular distortion. The explanation of this is given in Fig. 48, in which $O\ A$ and $O\ B$ indicate the directions of the principal meridians, $O\ B$ being that in which the image appears too large. The image of a square whose sides are obliquely inclined to the principal meridians would not be the square $A\ B\ C\ D$ but the oblique figure $A\ B_1\ C\ D_1$, for there is

an undue magnification in the direction *O B*, so that B_1 D_1 is a longer line than *A C*. Hence, the oblique line which would normally appear as *A B* appears in the distorted image as *A* B_1, which makes a greater angle with *A O* than *A B* does.

The degree of astigmia in the eye is slight as compared with the total refraction, and, consequently, the two focal lines are very near each other; hence, the actual distortion either with or without correction is not great.

Determination of the Axis of a Cylindrical Lens.—When a cylindrical lens is placed before the eye at a greater distance than that at which spectacles are worn, while a distant

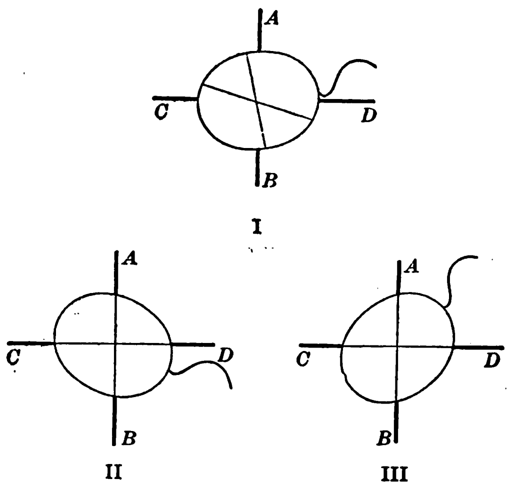


FIG. 49

Determination of the axis of a cylinder. A right-angled cross, *A B C D*, is seen through a glass containing a cylinder. If (I) the axis of the cylinder does not coincide with either *A B* or *C D* the cross will appear twisted, so that the arms no longer make a right angle. The cross, however, is not displaced as a whole either to one side or the other. If now the glass is rotated until the axis of the cylinder coincides with one arm of the cross—*e. g.*, *A B*. (II)—the cross will appear right-angled and unbroken. The same thing will happen if the glass is rotated 90° more (III), so that the axis of the cylinder coincides with *C D*.

object is viewed through the lens, the distortion may become very great. This property is used for the ready determination of the direction of the axis of a cylindrical lens. To find the position of the axis we hold the lens before the eye and look through it at a straight line across the room, as the edge of a test-card, rotating the lens in its own plane until we reach that position in which there is no break in the line, as seen through the lens and beyond its border (Fig. 49). The axis is then either parallel or

perpendicular to the line. If the length of the line is unaffected by the lens it lies in the direction of the axis, but if it is magnified or minified in length it lies at right angles to the axis; or if a movement of the lens in the direction of the line does not affect the apparent position of objects the line lies in the direction of the axis, but if such movement produces apparent displacement the line is at right angles to the axis. If the displacement is in the opposite direction to that of the lens, or if an oblique line appears to make a greater angle with the axis than really exists, the lens is convex; if the displacement is in the direction of motion of the lens, or if an oblique line appears to make a less angle with the axis than really exists, the lens is concave.

The following authorities have been consulted in the preparation of the foregoing chapter:

Borsch, *Lens, Encyclopaedia Americana.*

Airy, *On a Peculiar Defect in the Eye and a Mode of Correcting it,* Trans. Camb. Philos. Soc., 1827.

Burnett, *Treatise on Astigmatism.*

Heath, *Geometrical Optics.*

Donders, *Anomalies of Refraction and Accommodation.*

Landolt, *Refraction and Accommodation of the Eye.*

Duane, *Refractive Errors,* in Posey's *Diseases of the Eye.*

CHAPTER VII

OPTICAL PRINCIPLES OF OPHTHALMOSCOPY, SKIASCOPY, AND OPHTHALMOMETRY

In Fig. 50 *P P* represents the pupil of an eye under examination. Let us suppose first that the eye is myopic, so that *O* and *I* are conjugate points, as are also O_1 and I_1, and O_2 and

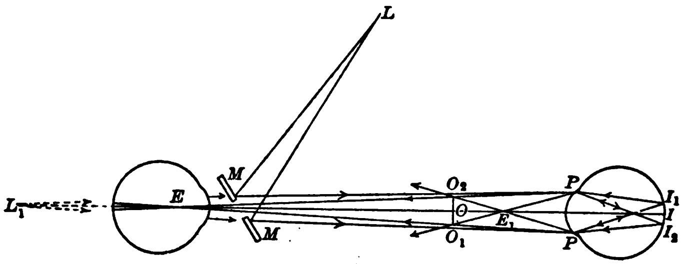


FIG. 50

Illustrating the path of the reflected and refracted rays in indirect ophthalmoscopy and in skiascopy. The rays emerging from the eye (*P P*) undergoing examination are rendered convergent by inherent myopia of this eye or by a convex lens placed in front of the eye.

I_2. Light from a point *L* is reflected into the eye *P P* by a plane mirror *M M*. The rays of light will enter the eye as if they diverged from L_1, as far behind the mirror as *L* is in front of it. Since L_1 is farther than the conjugate *O* from the eye, the rays will cross in front of the retina, and will form on the latter a diffusion image I_1 I_2.

Some of the light from the illuminated area I_1 I_2 undergoes irregular reflection and passes out of the eye. Of the light thus reflected, all rays which proceed from *I* must intersect at *O*; all which proceed from I_1 intersect at O_1; and all which proceed from O_2 intersect at I_2. There is formed, therefore, at O_1 O_2 a real inverted (aerial) image of the illuminated portion of the fundus.

If the flame were so placed that the light entered the eye as if diverging from *O*, conjugate to the retina, there would be no diffusion on the retina but a focused image of the point of light. If, on the other hand, the rays should diverge from a point nearer to *P P* than *O*, they would reach the retina before their union in a focus, and as before there would be a diffusion of light on the retina. *The area of illumination is therefore greater as the point of origin of the light is more removed from the conjugate to the retina.*

It is only in myopia that a real image of the illuminated area will be formed in front of the eye, for in emmetropia the emergent rays from any point of the fundus will be parallel, and in hyperopia the emergent rays will be divergent, and will appear to proceed from a virtual image behind the eye.

The size of the image in relation to the size of the illuminated area of the retina depends upon the respective distances of the two conjugates from the nodal point of the eye. Thus in axial myopia of 10 D the image is situated approximately at 107 *mm* from the nodal point, while the retina is about 19 *mm* from this point. The ratio $\frac{107}{19}$ gives us a magnification of about 5½ diameters. The magnification diminishes with the increase of myopia.

But the emergent rays in emmetropia and hyperopia may be united in a real aerial image in front of the eye by the aid of a convex lens. The position of the image will, of course, depend upon the strength of the lens used. The convex lens may also be used in myopia to bring the image nearer to the eye than it would be as formed by the eye alone.

In emmetropia the size of the image as formed by the convex lens is determined by the ratio of the anterior focal length of the eye to the focal length of the lens, irrespective of the position of the lens. In *axial hyperopia* and *myopia* the image has the same size as in emmetropia when the focus of the lens coincides with the anterior focus of the eye. When the lens is nearer than this the image is greater in hyperopia and less in myopia; when the focus of the lens is beyond the anterior focus of the eye the image is smaller in hyperopia and greater in myopia.

The reason that the pupil of the eye appears black under ordinary conditions and that we do not see the illuminated area of the fundus is that we have to place our head in such position

when we look into another person's eye that we intercept the light which would illuminate that part of the fundus lying in our line of vision. The path of the entering rays lies very near that of the emerging rays. This is most notably true in emmetropia. In hyperopia the rays diverge as they leave the eye, and in myopia they diverge after they have intersected in the aerial image. This is why the pupil sometimes is seen to shine in high degrees of hyperopia or myopia.

But in order that we may make practical use of the emergent rays for examining the fundus we must have a device which will allow these rays to enter the observer's eye without interfering with the illumination of the retina. Although *Brücke* in 1847 discovered the principles on which ophthalmoscopy is founded, the full explanation of them and their practical application by the invention of the ophthalmoscope is due to the genius of *Helmholtz* (1851).

The ophthalmoscope in its simplest form consists of a plane or concave mirror having at its center a small circular opening, through which light can pass to the eye of the observer. There must also be attached to the mirror a series of lenses to facilitate the focusing of the image.

Although the ophthalmoscope has been made in many different forms, the principle is the same in all. It is therefore unnecessary to describe the various stages of evolution through which this invention has passed. It suffices to say that Helmholtz did not use a silvered mirror, as we do now. He used a plate of plane glass, which reflected light into the eye under examination and at the same time permitted some of the emergent rays to pass through it and into the eye of the observer. We know that much of the light from the flame would pass through the plate of glass, and that the illumination of the fundus would be feeble. By using several plates Helmholtz sought to gain a greater reflecting power and better illumination of the fundus, but this method is much inferior to that which we now use.

Indirect Method of Ophthalmoscopy.—This method of examination consists in the examination of the aerial image as formed in front of the eye. The aid of a convex lens must be invoked in all conditions but the highest grades of myopia, since otherwise the image if formed at all, would be so far in front of the eye that, although highly magnified, only a very small

portion of the fundus would be visible. The power of the convex lens used may be varied at the convenience of the examiner. A lens of 13 D, which produces in emmetropia a magnification of about five diameters, is usually satisfactory. When we wish a greater magnification and in myopia a weaker lens may be used with advantage.

The lens should be held so that its focus lies in or near the plane of the iris of the eye under examination. The magnification of the pupil is then infinite or nearly so, the red reflex is coextensive with the lens, and the field of view is correspondingly large.

The examiner, looking through the sight hole of the mirror, may most easily see the details of the aerial image when he is at a distance of about 250 *mm* from this image. He may either use his accommodation to focus the rays diverging from the image, or he may make use of a convex lens attached to the ophthalmoscope for this purpose.

Direct Method of Ophthalmoscopy.—In the direct method the aim of the ophthalmoscopist is to approach the eye to be examined as near as is compatible with good illumination, and to receive directly upon his retina an inverted image of the illuminated fundus area. In this method the examiner's eye takes the place of the convex lens used in the indirect method.

In the diagram (Fig. 51) both examining and examined eyes

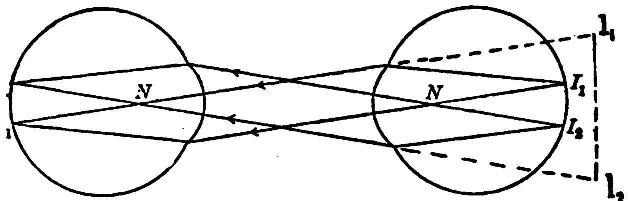


FIG. 51

are emmetropic. All the rays which emerge from any point of the illuminated area will be parallel, and some of the rays from the various points of this area will enter the examiner's eye and will be focused in an image on his retina without accommodation.

If the examined eye is myopic the emergent rays will be convergent (not yet having intersected in the aerial image) and in order that they may be focused by an emmetropic examiner

without accommodation they must be rendered parallel by a concave lens.

If the examined eye is hyperopic the emergent rays will be divergent and must be rendered parallel by a convex lens, or by exercise of the accommodation.

If the examiner's eye is ametropic his error may be corrected by the proper lens of the ophthalmoscope series, or he may use his ordinary eyeglasses.

Since an object is always inverted with respect to the retinal image, it is clear that in this method of examination the observer will see the fundus image in its natural or erect position. This image will appear to be behind the examined eye. We cannot assign any definite position to the image. To some persons it may seem to be quite near, while others will project it to a greater distance.

The apparent size of the image will, therefore, vary according to the position at which it is supposed to be. The actual magnification is due to the fact that in passing out of the examined eye the rays are rendered parallel (or approximately so if the eye is ametropic) and that by this means the examiner is able to focus them on his retina, and so to see the examined eye at a very short distance. In other words the eye under examination acts as a magnifying lens such as was described in the preceding chapter.

If we examine the diagram (Fig. 51) we see that when both eyes are emmetropic the retinal image as formed in the observer's eye is of exactly the same size as the fundus area under examination. We know that ordinarily the retinal image is much smaller than the object of vision, and we see that in this method of examination the image must be much magnified.

In estimating the magnifying power of microscopes it is customary to compare the size of the retinal image or the visual angle *as it is* with that which would be made by the same object on the retina if it were placed at the ordinary distance for examining small objects. Because of the limitation of our accommodative power we do not usually examine an object at a less distance than 10 inches or 250 millimeters. This distance is therefore taken as the standard of comparison in the measurement of magnifying power. With this understanding, the magnification under which the optic disk or any other part of the fundus is

seen in direct ophthalmoscopy is about 16 diameters, for the linear dimension of an object placed 256 *mm* from the nodal point of the normal eye would be 16 times as great as the corresponding dimension of its image on the retina.

In hyperopia the magnification is somewhat less, and it diminishes with the increase of the distance between the two eyes; in myopia the magnification is greater than in emmetropia, and it increases with the distance between the two eyes.

Skiascopy.

In the two preceding methods of examination it is the purpose of the examiner to see clearly the details of the fundus—in the one case by means of an inverted aerial image, and in the other by focusing the emergent rays directly upon his own retina. In the method now to be considered the object of the observer is not to see distinctly the details of the fundus-image, but to place his eye as nearly as possible in the position at which the aerial image of the examined eye would be formed, and to determine thereby the refractive condition of this eye.

Point of Reversal.—We have learned that the myopia of an eye is measured by the distance at which an object must be situated in order that it shall be focused on the retina without accommodation; that is, by the distance between the eye and its far-point. Since the retina and the far-point of an eye are conjugate, it is apparent that the aerial image is formed at the far-point, and that the position of this image determines the degree of myopia.

Since the emergent rays coming from any point of the fundus intersect in the aerial image, their relative position is reversed at this point. The point of reversal is therefore identical with the far-point of the eye.

Reversal of Movement.—If by tilting the mirror the illuminated area I_1 I_2 (Fig. 50) is shifted downward it is apparent that the aerial image O_1 O_2 will move upward, ***and if the examiner is farther than this image from the examined eye*** he may observe this movement, but if he is nearer the eye than the point of reversal, the aerial image O_1 O_2 will be replaced by the diffusion image on the examiner's retina, as in direct ophthalmoscopy. As the illuminated area I_1 I_2 moves downward the diffusion image on the examiner's retina moves upward, and

consequently there is an apparent downward motion of the illuminated area.

When therefore the examiner is *without* the point of reversal he sees the light area in the pupil move in an *opposite* direction to the actual movement of the light area on the fundus of the eye under examination; and when he is *within* the point of reversal he sees the light in the pupil move in the *same* direction as the movement of the light on the fundus.

The direction of the apparent movement of the light area is the basis of skiascopy, or the *shadow test,* which is our most reliable method for the objective determination of the refractive condition of an eye. In the application of this method the examiner's first aim is to determine whether he is within or without the point of reversal by watching the movement of the light area in the pupil of the examined eye while he varies the position of the light on the fundus by rotating the illuminating mirror.

When he is well within or without the point of reversal the examiner may readily see the fundus-image change its position; but when he is near the point of reversal he can see no details of the fundus, and he must decide as to the direction of motion by observing the variations of light and shadow in the pupil.

Variation of Magnification.—In the application of the direct method of ophthalmoscopy we may notice that in examining a myopic eye the magnification of the image increases with an increase of distance between the two eyes. In ophthalmoscopy this is not of any practical importance, because we do not to any

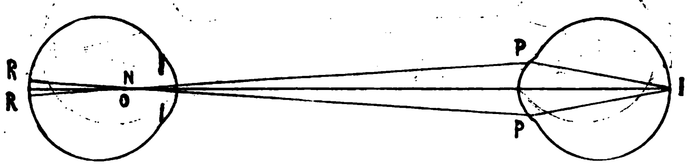


FIG. 52

great extent change the distance between the eyes. But in skiascopy in which the distance between the examined and the examiner's eye is greater, the varying magnification is a fundamental matter. The increase of magnification continues until the examiner's nodal point coincides with the point of reversal

of the eye under examination. At this point the magnification is *infinite*; or, to express it in more practical language, the single point I of the illuminated area will entirely fill the pupil P P of the eye under examination, as the examiner sees it. This is easily understood by an inspection of the accompanying diagram (Fig. 52).

We can also understand from Fig. 53 that when the examiner is at E_1, his retinal image of the pupil P P coincides, not with his image of a single point I as before, but with his

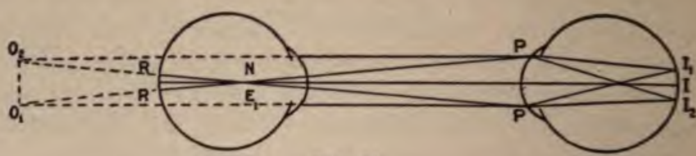


FIG. 53

image of the whole area I_1 I_2. In this case then the magnification is less, since a much greater part of the fundus-image will be seen. If he should approach still nearer the eye without enlarging the area of illumination on the examined eye, this area would no longer fill the entire pupil, which would therefore appear as a dark ring surrounding a bright center. Practically, however, as we get nearer the eye the area of illumination is increased, so that the entire pupil is ordinarily illuminated.

When the examiner is without the point of reversal, the magnification (which is now negative) diminishes, and if he is at E_2 (Fig. 54) his retinal image of O_1 O_2, corresponding to the

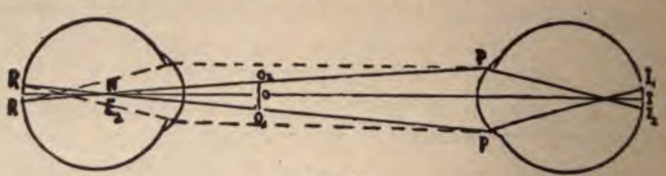


FIG. 54

area I_1 I_2, coincides with his image of the pupil P P, just as it did when he was at E_1.

Movement of the Shadow Line.—Let us again suppose the examiner's eye to be at E_2 and I_1 I_2 to be the illuminated area of the fundus. Under these conditions the entire pupil P P glows with the red reflex. If now the light area is shifted down-

ward by rotation of the mirror, so that the upper half $I\ I_1$ is no longer illuminated, the corresponding part $O\ O_1$ of the aerial image will be unilluminated—*that is, the lower part of the pupillary space will appear in shadow.*

As the area of illumination continues to move downward the shadow moves upward, and when the light has been shifted so far downward as to leave the entire area $I_1\ I_2$ in darkness, the image will have moved so far upward as to have passed out of the examiner's range of vision; that is, it will be above the pupil of the examined eye, and the latter will appear to the examiner to be in darkness.

The rapidity with which the shadow moves across the pupil varies with the examiner's position with reference to the point of reversal, being the more rapid as he approaches this point. When he is at this point the entire pupil glows as long as the single point I is illuminated, and when the light passes below I darkness quickly covers the pupil. When he is near, but not at the point of reversal, the examiner sees the shadow move very rapidly across the pupil as the light area is shifted by rotating the mirror.

When the examiner passes within the point of reversal (as at E_1) the shadow again begins to move more slowly, but now, as the light area moves downward, the *upper* portion of the pupil appears to be in shadow, and the border line between light and shade moves downward. It now moves in the same direction as the light area on the fundus of the eye undergoing examination.

In emmetropia and in hyperopia the examiner is always within the point of reversal. It is necessary, therefore, in the practical application of the shadow test to place a convex lens before the examined eye to bring the point of reversal to a convenient position.

Is the point of reversal governed by the position of the nodal point or of the pupil of the examiner's eye? In answer to this question we may say that practically it makes no difference which of the two we regard as the critical point. Since the nodal point and the pupil are in such close proximity as compared with the distance between the two eyes, it is of no importance whether we measure from the nodal point or from the pupil. From a theoretical point of view, however, the answer is not so easy.

In the explanation of the principles of this method of examination some European authors have maintained with plausible reasoning that the examiner's eye is at the point of reversal when his pupil (*not the nodal point*) is situated at the far point of the examined eye. For an explanation of this point of view let us refer to Fig. 52. Suppose that the light moves from I towards I_2. As it so moves the conjugate O moves upward, and the upper rays are cut off by the upper border of the pupil sooner than the lower rays. There will, therefore, be an apparent motion in the same direction as the light area, although the examiner's nodal point is at the point of reversal. If now he moves farther from the eye so that the conjugate O falls in the pupillary plane, all the rays will be intercepted at once, and beyond this point the rays will be reversed.

But if we accept this reasoning, which appears to be sound, we are confronted with another difficulty; namely, that it is only when the examiner's nodal point is at the conjugate O that the single point of light I fills the entire pupil P P. It is possible, therefore, that in the strictest sense there may be no absolute point of reversal.*

Form of the Shadow Line.—The light area on the retina will be circular, or approximately so, since the light is reflected by a circular mirror and enters the eye through a circular aperture, the pupil. The shadow edge must, therefore, correspond more or less closely to the arc of a circle. The curvature of this arc will vary with the portion of the outline of the light area which falls within the range of vision; that is, the edge will be more curved as the magnification is less, or according as the examiner is at a greater distance from the point of reversal. When he is near this point the border line of the shadow appears only slightly if at all curved.

Illumination of the Retina.—If a plane mirror is used to illuminate the retina, the apparent source of light is behind the mirror; but when the concave mirror is used an aerial image of the flame will be formed in front of the mirror, and this will be *the apparent source of illumination.* We readily see that with the plane mirror the motion of the apparent source of illum-

*This is upon the assumption that the illumination of the fundus is confined to a single point, which is never the case; it is apparent therefore that on this account and also because of spherical aberration there cannot be a single point of reversal for all the emergent rays.

ination is *opposite* to the direction of rotation of the mirror, while with the concave mirror the apparent source of illumination moves in the *same* direction as the rotation of the mirror. It is also evident that the motion of the light area on the retina is *opposite* in direction to the motion of the apparent source of illumination. *Therefore with the plane mirror the light area on the retina moves in the same direction as the tilting of the mirror, while with the concave mirror the light area moves in the opposite direction to the tilting of the mirror.*

We have so far regarded the illuminated area I_1 I_2 as the same in the various positions of the examiner; but in reality when he changes his position he also changes the position of the mirror and with it the apparent point of origin of the illuminating rays. We have learned that with the same source of illumination the light area on the fundus is more diffused according as the point of origin of the rays is more remote from the point of reversal. Therefore, in order that we may have a bright, well focused light area, giving a sharp contrast between light and shade, we should so arrange the light that as the examiner approaches the point of reversal the apparent source of illumination should also be near this point. This may be most conveniently accomplished by having a small electric lamp attached to a plane mirror, so that the apparent source of illumination is a short distance behind the mirror.

Two Points of Reversal in Astigmia.—In regular astigmia there is a separate point of reversal for each principal meridian, and when the examiner is at this point for one meridian he will be remote from that for the other principal meridian, the more so according as the astigmia is greater. The rate of the shadow movement will therefore be different in the two principal meridians. If this movement is such as to indicate that the examiner is at the point of reversal in one meridian there will be a well defined shadow motion in the other meridian, and this will be with or against the motion of the light area according as in the second meridian there is less or more refraction than in the first meridian.

Rectilinear Shadow Lines in Astigmia.—The appearance of a band of light bordered by a straight shadow edge is indicative of astigmia. This effect is produced when the examiner is at or near the point of reversal for one principal

meridian. When he is at this point the magnification is infinite as regards this meridian, but it is less in the other meridian. Therefore the circular or oval light area will be so magnified in the first meridian without a corresponding magnification in the second meridian that it will appear in the pupil as a band of light extending entirely across the pupil in the more magnified meridian. Since the magnification is infinite in this direction, the lines which separate the light from shade must appear as straight lines.

The band of light is most distinctly seen when the apparent source of illumination is conjugate to the fundus in the meridian in which the shadow appears. With the plane mirror this arrangement is effected when the observer is at the point of reversal nearer to the eye while the image of the flame is at the more remote point of reversal (*Jackson*).

Summary of Underlying Principles of Skiascopy.— The practical application of the shadow test, which will be considered in a subsequent chapter, does not ordinarily present any great difficulty; but the optical principles involved, which I have endeavored to explain, require very careful study that they may be properly understood. The following summary gives the more important points to be borne in mind.

(1) *The point of reversal* corresponds to the far point of the eye, either alone or in combination with a lens. If the eye is not myopic a convex lens must be placed before it so as to bring the point of reversal to a convenient position.

(2) *When the examiner is within the point of reversal* the shadow line moves in the *same* direction as the tilting of the mirror if this is plane, and it moves in the *opposite* direction if the mirror is concave.

(3) *When the examiner is without the point of reversal* the shadow line moves in the *opposite* direction to the tilting of a plane mirror, and in the *same* direction as the tilting of a concave mirror.

(4) *When the examiner is remote from the point of reversal* the movement is slow and the shadow is dense; when he is near the point of reversal the movement is rapid and the shadow is faint.

(5) *A bright band of light* bordered by a straight shadow edge is characteristic of astigmia.

Ophthalmometry

Although the word *ophthalmometry*—measurement of the eye—is etymologically coextensive with optometry, its use is restricted by custom to the actual measurement of the curvature of the refracting surfaces.

When rays of light impinge upon the cornea, they for the most part penetrate this substance, but, as we have learned, some of the light is reflected; the surface of the cornea acts as a convex mirror, and a small, erect, virtual image of the illuminating object is formed by the reflection (Fig. 55). Similarly, when the light reaches the posterior surface of the cornea a small

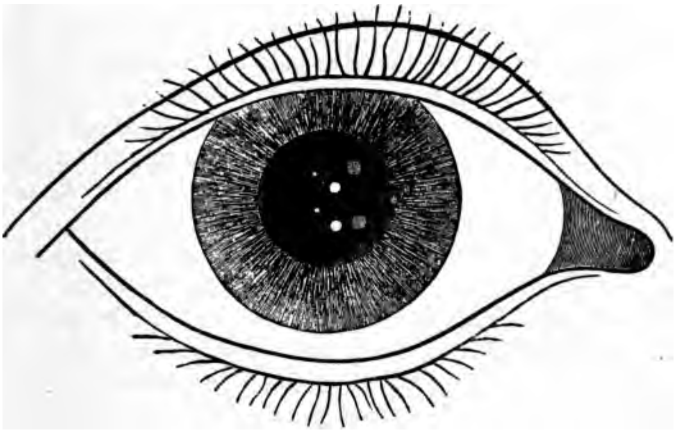


FIG. 55

The Images of *Purkinje* (*Tscherning*)

The corneal images in the middle; the images of the anterior surface of the crystalline lens on the right; those of the posterior surface of the crystalline lens on left. The images reflected from the posterior surface of the cornea are not visible.

portion is turned back by reflection. Owing to the fact that the difference of refractive index between the cornea and the aqueous humor is slight very little light is reflected at the posterior surface of the cornea, and the image is correspondingly faint.

At the anterior surface of the crystalline lens still another reflection occurs, and again we have a virtual image produced by the reflection at the convex surface of the lens. Finally a real inverted image of the illuminating object is formed by reflection from the posterior surface of the lens, which acts as a concave mirror.

The ophthalmometer is a contrivance for measuring the curvature of the refracting surfaces of the eye by means of the *images of Purkinje,* which have just been described.

In order that we may make use of the reflected images for measuring the curvature of the surfaces we must examine the images through a magnifying apparatus. This apparatus is called the *telescope* of the ophthalmometer, although it does not conform to the technical definition of a telescope.*

The first attempt to measure the curvature of the anterior surface of the cornea by means of the reflected image was made by *Home* and *Ramsden* (1795) in their endeavor to ascertain whether there was an increase of curvature of the cornea in accommodation. They used for this purpose a microscope of low power, in the eyepiece of which they placed a micrometer scale for the measurement of the image. Later *Kohlrausch* (1839) undertook to measure the radius of the cornea in a number of eyes, using the same method. The results were not satisfactory, however, since it is impossibe for an eye to remain immovable during the process of measurement.

Helmholtz, therefore, who devised the first successful ophthalmometer (1854), used, in measuring the radius of the anterior surface of the cornea, the method of doubling the image —a method which has long been used in astronomical work.

By looking through a double prism (with one eye excluded) at a drawing such as *A B* (Fig. 56) one can easily understand

FIG. 56

how the principle of doubling the image is applied in ophthalmometry. When the prism is properly placed before the eye two images of *A B* appear. The amount of separation between the two images varies with the distance of the prism from the

*A telescope is an optical instrument so constructed that the parallel entering rays are also parallel when they emerge from the apparatus. It is therefore a contrivance for examining distant objects, while a magnifying apparatus for examining near objects is called a microscope.

line *A B*, and by suitable adjustment of this distance the observer may bring the double images into contact, as is shown in Fig. 57. It is apparent that in this condition the amount of displacement produced by the prism is exactly equal to the length of *A B*. If therefore we know the strength of the prism and the position at which the contact image is formed, we can determine the distance between *A* and *B*. If, for instance, we are using a one

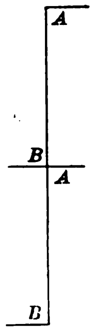


FIG. 57

diopter prism (each of the component prisms having one-half of this power), and the contact position occurs at a distance of one meter, we know that the length of *A B* is $\frac{1}{100}$ of a meter, as follows from the definition of a prism diopter. If the contact position should occur at a distance of two meters, the length of the line *A B* would be $\frac{2}{100}$ of a meter (2 *cm*), and so on for other distances of the contact position.

When we use a doubling device in ophthalmometry we copy the foregoing procedure. The ophthalmometer is provided with two small luminous objects, called *mires*, the reflected images of which we examine in the telescope of the ophthalmometer, and by the proper manipulation of the instrument we get the contact position as shown in Fig. 57.

Helmholtz obtained the double images in his ophthalmometer by means of two plates of glass inclined at an angle which could be varied by the operator.* Thus instead of changing the position of the prism, as in our illustration, he changed the doubling power of the plates by varying their inclination.

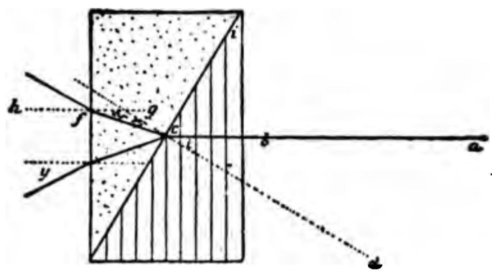
*Two plates of glass inclined at an oblique angle produce double images by means of the lateral displacement which the rays undergo on account of the thickness of the glass.

Helmholtz's apparatus served a very useful purpose, but because of the great distance (about six feet) between the examiner and the eye under examination, and because there was no ready means of finding the meridians of greatest and least refraction, this ophthalmometer was suitable only for laboratory investigations, and not for the measurement of corneal asymmetry—the purpose for which modern ophthalmometers are designed.

The means by which *Javal* and *Schiötz* (1882) made ophthalmometry a practical method for the ready determination of corneal asymmetry consisted in the shortening of the focal length of the telescope; in the adoption of mires which quickly reveal the meridians of greatest and least refraction; and in having the various parts so proportioned and arranged that the amount of astigmia in diopters is shown to the examiner without any preliminary calculation.

In the *Javal-Schiötz* ophthalmometer the doubling is produced by the *Wollaston* prism of quartz—a substance which has the property of polarizing light and producing double refraction.

The Wollaston prism consists of two prisms of quartz properly cut with reference to the polarizing axes and cemented together (Fig. 58). Each ray which passes through the prism



Wollaston Prism

FIG. 58

is divided into two rays, as shown in the illustration, so that an object seen through the prism appears double.

The telescope of this ophthalmometer consists of an eyepiece and a double objective, the birefringent prism being placed between the two lenses of the objective. Since this prism occupies a fixed position its doubling power cannot be varied. The contact position of the double images must therefore be gotten

by making the size of the image conform to the fixed doubling power of the prism.

Each lens of the objective has a focal length of 270 *mm.* The image under examination is at the principal focus of the first lens. Rays reflected from any point of the cornea will be parallel after passing through this lens. They then enter the *Wollaston* doubly refracting prism, and are divided into two sets (each of which gives an image); they are then further refracted by the second lens of the objective, and are focused at a distance of 270 *mm* from the lens; for the rays, having been rendered parallel by the first lens, must now be focused at the principal focus of the second lens. Since the objective as a whole thus occupies the midway position between the two conjugate foci, we see that the image as formed at the focus of the eyepiece must have the same size as the image formed by reflection at the cornea. But the image at the eyepiece has been doubled by the prism, and if the separation between these two images can be made equal to the diameter of the image, the two images will be seen in the contact position. The prism, as used in this instrument, causes a separation of about 3 *mm,* and by altering the distance between the mires we can make this distance such that the image as reflected from the cornea exactly equals the amount of separation, and the two images will then be seen in the contact position.

When we have by this means determined the size of the corneal image, we can deduce the radius of curvature of the cornea which corresponds to this image. By determining this curvature in the two principal meridians we find the amount of astigmia which results from any existing corneal asymmetry.

The method adopted by *Javal and Schiötz* for marking the principal meridians and measuring the asymmetry is shown in

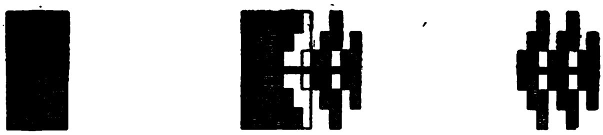


FIG. 59

Fig. 59. One of the mires is a rectangle and the other consists of a series of rectangular steps. A straight black line runs through the middle of each mire.

When the plane of deviation of the prism corresponds with either one of the principal meridians the two images retain their rectangular form and the line running through one mire forms a continuation of that running through the middle of the other. But in any oblique meridian the rectangles are distorted so as to appear as oblique parallelograms, and the middle lines are not continuous with each other. This phenomenon of toric reflection is analogous to what we learned in studying toric refraction. As we then saw that rays meeting the toric surface in an oblique meridian would not lie in a common meridian after refraction, so it is with the reflected rays. The reflected images of the two mires will not lie in a common

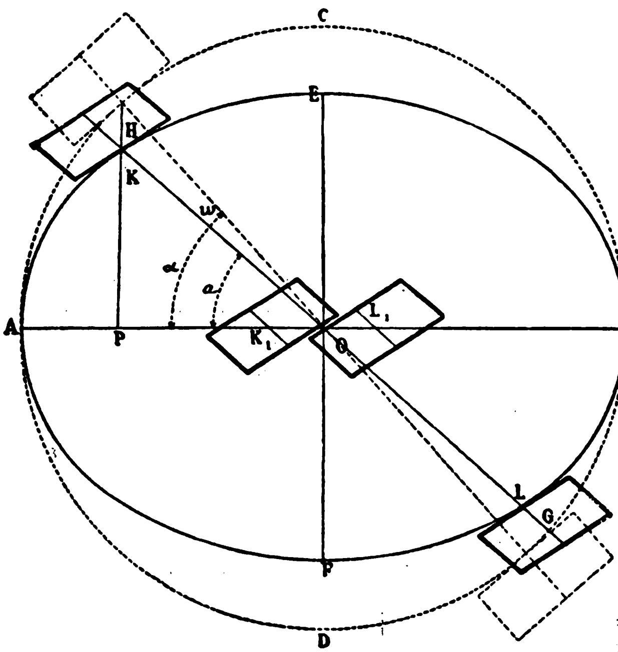


FIG. 60
Explanation of the Difference in Level (*Tscherning*)

meridian; one of the images will be higher or lower than the other. This is illustrated in Fig. 60.

If the cornea is symmetrical, the images appear as in the dotted outline; that is, in any meridian in which the mires may

be placed, their outside double images are always tangent to the circle of the dotted outline. But when the cornea is asymmetric the images are smaller in the meridian of greatest curvature than in that of least curvature, and as the mires are revolved from one principal meridian to the other the outside images (*H* and *G*) describe an ellipse as in the diagram, and since the doubling takes place in the plane of the prism, the middle lines of the two inside images (*K* and *L*) do not now lie on the diameter of the circle, but lie on opposite sides of this diameter. *The principal meridians are therefore marked by the two directions in which the lines passing through the middle of the mires appear to be a continuous line.*

The series of steps, as used in one of the mires, was devised for the ready measurement of astigmia. The image which corresponds to each step is regarded as representing one diopter of refraction. This is only approximately true, since the proportion of the mire which corresponds to one diopter varies with the radius of curvature. Each step corresponds to one diopter when the reflected image is 2.94 *mm* in diameter. When, therefore, there is an overlapping of several steps the image is less than 2.94 *mm,* and the steps do not accurately measure the number of diopters of astigmia. In the lower degrees of asymmetry we may rely upon the overlapping of the steps, but in the higher degrees we obtain a more accurate result by reading from the scale attached to the instrument.

With the addition of modern mechanical adjustments the *Javal-Schiötz* ophthalmometer surpasses all other instruments of this kind in the accuracy of its measurements.

An extended experience with the various devices for doubling the image has convinced me that the Wollaston prism alone of the available means can be relied upon to give a sufficiently accurate result for the measurement of small degrees of corneal astigmia.

I base this opinion upon the results of my own practice with the artificial cornea as well as upon the results which I have seen in the attempts of several skilled manipulators to mark the contact position in repeated measurements by a uniform position of the pointer on the recording scale.

The inaccuracy which results from the use of the glass doubling devices is due chiefly to the fact that when they are used the depth of focus is greater than with the quartz prism. When the latter is used the slightest error of adjustment produces a blurred image; whereas, with the former the adjustment of the instrument (or the position of the eye under examination) may be so varied as to affect very materially the doubling action of the prism without marring the sharpness of the image. An

error of .50 D or more may readily be made from this cause by a careful observer.

Javal and Schiötz placed the prism of their instrument between the two lenses of the objective in order that the rays from any point of the image would be parallel in passing through the prism, for, as we have learned, parallel rays do not undergo the relative distortion to which divergent or convergent rays are subject in traversing a prism.

A double prism of glass affords a greater intensity of illumination than does the quartz prism. With the former we may use a small aperture and obtain clear images by placing the prism between the objective and the eyepiece. With this arrangement the mires may remain stationary while the contact position is obtained by moving the prism in the tube of the telescope, as in the *Chambers-Inskeep ophthalmometer.*

Of other appliances for measuring the curvature of the anterior surface of the cornea only the *keratometer of Sutcliffe* requires especial mention. The unique feature of this instrument is that the curvature is measured simultaneously in the two principal meridians of the cornea. There are two pairs of mires and each pair is doubled in its own meridian. The doubling is accomplished by means of movable cylindrical lenses of weak power which are placed between the two lenses of the objective. As these cylinders are moved transversely they present varying degrees of prismatic action.

Keratometry and Phakometry.—*Helmholtz* designed his ophthalmometer not only for measuring the anterior surface of the cornea, but for measuring also, though by a more complicated process, the two surfaces of the crystalline lens. *Javal and Schiötz,* on the other hand, intended their instrument solely for measuring the curvature of the anterior surface of the cornea. It is not, therefore, in the fullest sense, an ophthalmometer, for ophthalmometry includes both *keratometry* (measurement of the cornea) and *phakometry* (measurement of the lens). So also other modern ophthalmometers are designed for measuring corneal astigmia only, and they are sometimes called *keratometers.*

From a practical standpoint keratometry is more important than phakometry, for the main cause of the higher degrees

of astigmia is found in asymmetry of the anterior surface of the cornea. But phakometry also has its usefulness, for in the lower degrees of astigmia no reliable information is furnished by keratometry except in conjunction with phakometry.

With his *ophthalmo-phakometer Tscherning* has been enabled to measure the curvature of the posterior surface of the cornea and of the two surfaces of the crystalline lens. But as several difficult observations must be made, and the curvature deduced from trigonometrical calculation, this method is suitable only for laboratory investigations.

I have had an ophthalmometer constructed with which I can apply the method of doubling to the direct measurement of the two surfaces of the crystalline lens. The basis of this apparatus is the *Javal-Schiötz* ophthalmometer. But in order that this may be adapted for measuring the two surfaces of the lens as well as the anterior surface of the cornea, two radical changes in construction are required.

The first of these innovations is in the mires, in order that sufficient illumination may be secured for the lens measurements. The opalescent glass is made readily removable by means of a rotating disk, so that in measuring the lens the unshaded filaments of two small electric lamps are used as mires.

The second innovation is required in order to adapt the instrument to the great variation in the size of the images as formed at the posterior surface of the lens and at the anterior surface with magnification by the cornea. We must provide for a variation in radius of curvature from 5 *mm,* for the posterior surface of the lens, to 20 *mm,* which represents the apparent radius when the actual radius of the anterior surface is 12 *mm.*

The adaptation of the instrument to this great variation of curvature is accomplished by making the objective and the prism movable in the tube of the telescope. By varying in this way the relative size of the image at the eyepiece as compared with the actual image under measurement, the images formed at all three surfaces can be measured. The required movement of the objective is not so great as to mar the sharpness of the images because of divergency or convergency of the rays as they traverse the prism.

The images formed at the anterior surface of the lens are diffuse and indistinct, and a slight movement of the eye throws them out of view. It is therefore not easy to measure the curvature of this surface; in fact it is not possible without intelligent co-operation on the part of the examinee. Furthermore we cannot determine with exactness the real from the magnified image unless we know the position of the surface, which is not determined in this method. The measurement of the anterior surface is therefore an approximation, which is based upon an average curvature of the cornea and an average depth of the anterior chamber; but as we need know only the difference in curvature in the two principal meridians for the determination of astigmia, and as a decided difference of curvature causes only a slight degree of astigmia at this surface, the accuracy attainable is sufficient for practical purposes. In fact, as I shall show in the further consideration of this subject in the appendix, the anterior surface of the lens is a subordinate factor in the production of astigmia.

The posterior surface of the lens is so situated with reference to the refractive properties of the eye that the reflected images are not altered in size by refraction. These images are distinct, and we can therefore measure the posterior surface with accuracy.

Determination of Astigmia by Ophthalmometry.—By means of the measurement of the curvature of the cornea or lens, we may determine the astigmia which results from asymmetry of any of these surfaces. We do this by expressing the reciprocal of the anterior focal length as the dioptric equivalent in each of the meridians measured, and by taking the difference between the dioptric equivalent in the two principal meridians. This difference represents the dioptric power of the correcting lens as applied directly to the surface under measurement. We ordinarily neglect the error which we incur from the fact that the correcting lens cannot be placed in contact with the cornea, although this error is at times very considerable.

The method of determining the astigmia from the ophthalmometric observations will be more fully explained in the appendix. It suffices to say here that in estimating the focal length of the cornea we do not assign the index of the cornea, but that of the aqueous humor. If, as is probable, the posterior surface

of the cornea follows the asymmetry of the anterior surface, we incur no appreciable error by doing this and neglecting the posterior corneal refraction. *Tscherning* thinks, however, that the curvature of the posterior surface of the cornea is almost invariably greater in the vertical than in the horizontal meridian. If this is true an error in the measurement of corneal astigmia results when the curvature of the anterior surface of the cornea is greatest in the horizontal meridian.

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PART II

THE NORMAL EYE

CHAPTER VIII

THE REFRACTIVE MECHANISM

In order that we may investigate understandingly the refractive properties of the eye we must be familiar with the essentials of the anatomy of this organ.

The normal eyeball (Fig. 61) is nearly spherical in shape. The antero-posterior diameter is the greatest; the vertical diameter is the least. The former measures from 23 *mm* to 25 *mm;* the latter from 22 *mm* to 24 *mm.* We may, therefore, with sufficient accuracy for a general description, say that the eyeball is a globe whose diameter is about one inch.

If we view the eye externally we see that it consists of two distinct portions: an anterior, transparent portion, *the cornea;* and a posterior, larger, opaque portion, *the sclera.* The curvature of the cornea is greater than that of the sclera, so that the junction of these two structures is marked by a groove or sulcus —*the sulcus of the cornea.* Of an antero-posterior meridional section of the eyeball, the cornea comprises about one-sixth, and the scleral portion the remaining five-sixths.

The eye is protected posteriorly by the bony walls of the orbit, in which it lies, but anteriorly its only protection is that afforded by the lids. The latter serve, when partially or completely closed, to protect the eye from excessive light, and from injury by foreign bodies.

The inner surface of the lids is covered with mucus-membrane, the ***conjunctiva,*** which is reflected at the upper and lower fornices (***culs-de-sac***) upon the eyeball, and the epithelium of this membrane is continued over the anterior surface of the

cornea. The conjunctiva thus forms a sac, open anteriorly at the lid-margins.

There are three concentric coats or tunics of the eye. These are called the *external,* the *middle,* and the *inner* coat.

The External Coat.—The external coat consists of the cornea and the sclera. The structure of these two membranes is essentially the same, both being composed of fibrous tissue.

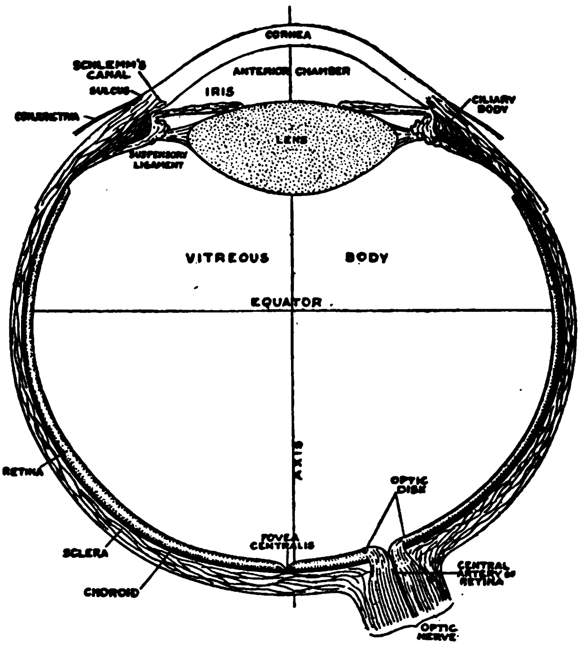

FIG. 61

Normal Eyeball (diagrammatic); Section in the Horizontal Meridian.

The transparency of the cornea results from the close union and regular arrangement of the fibers, and from the homogeneous composition of its tissues.

The cornea is covered anteriorly with epithelium which is continuous with that of the conjunctiva. Immediately behind the epithelium is the anterior limiting membrane, *Bowman's membrane,* which is a dense, structureless membrane. Behind this is the corneal tissue proper, the *stroma,* which consists of regularly arranged lamellæ of fibrous tissue. Between the

bundles of fibers there are lymph spaces or *lacunae* which are connected with each other by small canals or *canaliculi.* Each lacuna contains a cell whose processes extend along the canaliculi to neighboring cell-processes, so that there is a general intercommunication between the various cells. These cells are called the *fixed cells* of the cornea, in contradistinction to the movable cells or *leucocytes,* which are carried through the lymph channels. The fourth layer of the cornea is *Descemet's membrane,* a thin, homogeneous, resistant structure, which is a part of the middle coat of the eye. The fifth and last layer of the cornea is *the layer of endothelium* or polygonal cells, which, like the preceding, is a part of the middle coat of the eye.

There are *no blood vessels* in the healthy cornea; nourishment is supplied by the lymph channels.

The *corneal nerves* are derived from the ciliary plexus. They form a network around the corneal margin from which branches are given off to supply the several layers of the cornea.

The sclera differs in structure from the cornea in that its fibers are irregularly arranged. It is of a white, glistening color, which shows that its blood supply is scanty. The sclera is pierced by a number of openings for blood vessels and nerves. The largest of these, which is for the entrance of the optic nerve and retinal vessels, is about 1.5 *mm* in diameter. It is situated slightly to the nasal side of the posterior pole of the eye.* This opening is traversed by connective tissue fibers, the *lamina cribosa.* The outer layers of the sclera are continuous with the sheath of the optic nerve.

The greatest thickness of the sclera is in the region of the posterior pole, where a thickness of 1 *mm* is attained. From this region it becomes thinner towards the equator, and it is again thickened anteriorly where the sclera is blended with the insertions of the ocular muscles.

Near the sclero-corneal junction, and concentric with it, there is a circular canal, *Schlemm's canal,* which is a venous channel.

The sclera is covered externally by a thin layer of loose connective tissue, the *episclera,* which is more freely supplied with blood vessels than is the sclera itself.

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*The points where the optic axis intersects the circumference of the eyeball are regarded as the poles.

The anterior portion of the sclera is covered by conjunctiva; the posterior portion is embedded in a fibrous capsule (*Tenon's capsule*), in which it is freely movable.

The Uvea.—The middle coat is called the *uvea,* from its resemblance, when stripped from the sclera, to a grape.

The iris or anterior portion of the uvea is a diaphragm which has at or near its center a circular opening, the *pupil,* for the passage of light to the retina. From the pupillary border the iris extends peripherally to the ciliary body, to which it is attached at a short distance behind the sclero-corneal junction. The angle between the sclero-cornea and the iris is bridged over by loose spongy tissue which is called the *ligamentum pectinatum.* The patulency of this structure is of great importance in the regulation of intraocular tension, for it is through its meshes that the aqueous humor is drained into Schlemm's canal, of which the ligamentum pectinatum forms the inner wall.

The iris is composed of an *endothelial layer* in front, a *pigment layer* behind, and, between these two layers, the *stroma.* The stroma is a net-work of blood vessels, and fibrous tissue, in which are embedded the two muscles of the iris, the *sphincter* and the *dilator pupillae.* The former is a circular band of fibers about 1 *mm* in width, which surrounds the pupil and causes contraction of this opening. The dilator muscle consists of radial fibers which assist in dilating the pupil.

The bluish color of the iris in blondes is caused by light reflected from the pigment contained in the posterior or pigment layer. In dark eyes there is also pigment in the stroma of the iris.

The ciliary body, or middle portion of the uvea, is a ring-shaped body, which surrounds the inner surface of the sclera, extending from the sclero-corneal junction backward for about 2 *mm,* where it becomes merged with the choroid. This body, which is of importance in the study of accommodation, will be more fully considered in connection with that subject.

The choroid is that part of the uvea which is posterior to the ciliary body. Its color is dark brown; it thus differs from the ciliary body, the inner surface of which is black.

The choroid is a very thin membrane, being only about .1 *mm* at its thickest part, which is near the optic nerve. In structure

it consists of a net-work of blood vessels, connective tissue, and pigment.

The blood supply is derived from the anterior and posterior ciliary arteries. After circulating through the capillaries the blood leaves the eye through the *venae vorticosae,* of which there are from four to six penetrating the sclera in the equatorial region.

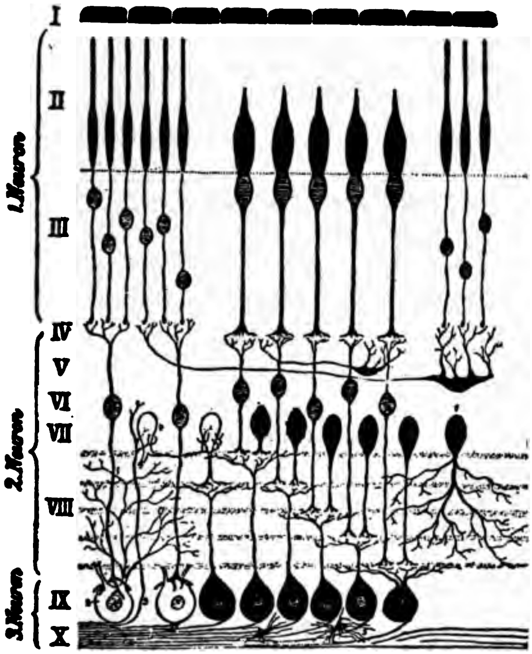


FIG. 62

Diagram of the structure of the human retina according to Golgi's method. (*Greeff.*)

I, Pigment layer; II and III (1 neuron), the neuro-epithelial layer; IV, V, VI, VII, and VIII (2 neuron), the bipolar cells, and other cells whose function is unknown; IX and X (3 neuron), ganglion cells and nerve fibers.

The nerves of the uvea are branches of the long and short ciliary nerves. The long ciliary nerves are derived from the nasal branch of the fifth nerve. The short ciliary nerves arise from the ciliary ganglion. They contain motor fibers from the third nerve, sensory fibers from the fifth, and sympathetic fibers from the sympathetic system.

The Retina.—The third or inner eye tunic is called the

retina. It is formed by the expansion of the optic nerve. The nerve fibers within the eye consist only of transparent axis-cylinders, except in the anomalous condition of *opaque nerve fibers.* The fibers radiate from the optic disk or entrance of the nerve so as to form the inner layer of the retina. The optic disk is situated slightly to the nasal side of the posterior pole of the eye. The area which the disk covers constitutes *Mariotte's blind spot,* there being at this place no terminal elements capable of exciting vision.

The macula lutea or yellow spot, situated about 3 *mm* to the outer side of and a little below the optic disk, is an annular or elliptical area from 1 *mm* to 2 *mm* in diameter. At its center there is a minute depression, the *fovea centralis.*

The retina extends forward as far as the *ora serrata,* beyond which it is rudimentary. In the latter condition it furnishes the posterior pigment layer of the ciliary body and iris, which is continuous with the pigment layer of the retina.

In structure the inner tunic consists of the supporting neuroglia, or *sustentacular tissue of Müller,* and the retina proper. The latter is composed of two laminæ; an outer *pigment layer,* and an *inner layer of nerve tissue.* The nerve tissue is divided into the *neuro-epithelial layer* and the *cerebral layer.*

The neuro-epithelial layer consists of the retinal rods and cones, which form the light-receiving and transforming mechanism.

The cerebral layer, by which the impulse received by the rods and cones is transmitted to the brain, contains a layer of bipolar cells, a layer of ganglion cells, and nerve fibers. The bipolar cells connect the rods and cones with the ganglion cells of the nerve fibers. They thus form a connecting link between the peripheral recipient elements and the conducting nerve fibers (Fig. 62).

The macula lutea, so called from its yellow appearance when anatomically examined, is the part of the retina which is concerned in distinct vision. In this region the rods are replaced by cones, the latter being much more numerous than in other parts of the retina. The depression at the fovea centralis is due chiefly to the thinning of the nerve fiber layer (ganglion cells) and to the sessile character of the bipolar cells.

The blood supply of the outer layers of the retina is derived from the capillaries of the adjacent choroid. The inner layers are supplied by the branches of the *central artery of the retina.* The veins which carry the blood from the retina follow the same general course as the retinal arteries. There are no large vessels at the macula (Fig. 63), but this region is richly supplied with capillaries, except at the fovea, where there are no vessels.

FIG. 63
Blood-vessels of the retina (*Henle*).

Contents of the Eyeball.—There are enclosed by the tunics of the eye the *aqueous humor,* the *crystalline lens,* and the *vitreous* body. These substances serve to distend the tunics so as to give shape to the eyeball, and at the same time they serve as refractive media. As we are concerned with them chiefly as refractive media they will be described as such under the following caption.

Surfaces and Media of the Eye.—As we have already learned, the anterior surface of the cornea is the most effective of the refracting surfaces of the eye. The form of this surface has been very carefully studied by many investigators since the introduction of ophthalmometry by *Helmholtz.* As the measurement of this surface with *Helmholtz's* ophthalmometer was a laborious procedure, the number of observations was not nearly so great as have been more recently made with the *Javal-Schiötz* instrument. Prior to the invention of this ophthalmometer it was customary to regard the normal cornea as resembling the

small end of an ellipsoid as formed by revolution about its long axis. The measurements which had been made were sufficient to show that the cornea, like the ellipsoid, had a greater curvature at the center than at the periphery. But when more numerous measurements at various distances from the center were afterward made with the *Javal-Schiötz* ophthalmometer, it was learned that the cornea as a whole could not be compared to any symmetrical surface.

The following conclusions have been reached by *Sulzer* as to the form of the cornea:

(*a*) *The central region of the normal cornea differs but little from a segment of a sphere.*

(*b*) At a distance of about 2 *mm* from the point of intersection of the visual line with the cornea the curvature begins abruptly to diminish. From this point to its periphery the corneal surface shows a progressively decreasing curvature.

(*c*) Whether we regard the point of intersection of the visual line with the corneal surface, or the point of maximum curvature as representing the center of the cornea, the curvature does not diminish proportionally to the distance from this center. This is true whether the distance is measured on the two principal meridians or on the two halves of the same meridian; in other words, the cornea is not in any sense a surface of symmetrical curvature.

The average radius of curvature of the central portion of the cornea is, according to *Helmholtz*, 7.829 *mm*. Other averages do not differ materially from this, and a radius of 7.8 *mm* may be accepted as the standard for the normal eye. The limits within which the radius varies in emmetropia are comprised (as determined by *Schiötz* from a large number of examinations) between 7.2 *mm* and 8.6 *mm*. The variations of curvature in a number of measurements by *Tscherning* are shown graphically in Fig. 64.

The curvature of the posterior surface of the cornea follows, in general, that of the anterior surface, but it approximates somewhat more nearly the spherical form. The average radius of curvature, as ascertained by anatomists and by *Tscherning*, is 6 *mm*.

The thickness of the central portion of the cornea is about 1 *mm* (*Tscherning* and others).

The refractive index of the cornea, as determined by *Aubert,* is 1.377. Other estimates differ but slightly from this.

Helmholtz, in his schematic eye, adopted 1.3365 as the common index of cornea, aqueous, and vitreous.

The distance of the retina from the anterior surface of the cornea in this schematic eye is 22.8 *mm;* whereas in my calcula-

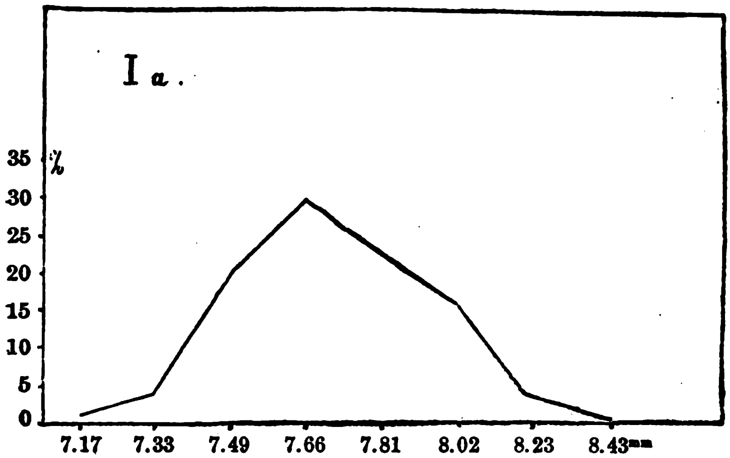


FIG. 64

The abscissas indicate the radii of curvature of the cornea in millimeters, the ordinates the number per hundred of emmetropes in whom we meet the radius of curvature (*Tscherning*).

tion, which is based upon four refractions, the corresponding distance from the cornea to the retina is 23.2 *mm.*

The aqueous humor occupies the space (*the anterior chamber*) between the cornea and the crystalline lens. The aqueous, being fluid, must be enclosed in a solid receptacle in order that its index may be determined. A small quantity of the aqueous may be placed at the apex of two inclined plates of glass; or it may be enclosed in a hollow lens (*Helmholtz*). The refractive effect of the glass being known, the remaining refraction which occurs in the passage of light through the combination represents the effect of the aqueous humor, from which the index can be derived by calculation. The index, as determined by *Helmholtz,* is 1.3365; *Fleischer* gives 1.3373 as the average index. An index of 1.337 may be accepted as the standard.

The transparency of the cornea and aqueous humor, as direct inspection shows, is almost perfect. This transparency is attained in the cornea by the great regularity and close union of the individual lamellæ, and by the interposition of a cement substance of the same index as that of the lamellæ; otherwise reflection from the various strata would interfere with the passage of light. In health it is only by the most careful examination that we are able to detect any such reflection, but when the physiological arrangement is disturbed by disease, the cornea loses its transparency.

Much greater difficulty has been experienced in determining the exact form of *the surfaces of the crystalline lens* than in determining the form of the cornea; but measurements made by *Helmholtz, Donders, Knapp,* and others—which have recently been substantiated by *Tscherning*—show that, *the ciliary muscle being relaxed,* the central portion of the anterior surface does not materially differ from a segment of a sphere having a radius of 10 *mm,* and that the corresponding portion of the posterior surface equally resembles a segment of a sphere having a radius of 6 *mm.** Since only the central portions of these surfaces are concerned in normal vision, we may in our calculations assume that they are spherical.

From a number of anatomical measurements, made prior to the era of ophthalmometry, *Brücke* concluded that the anterior surface of the lens corresponded approximately with the surface generated by the revolution of an ellipse about its minor axis, while the posterior surface approximated a paraboloid of revolution. Although neither surface is a true geometrical curve, *Brücke's* conclusions have, in general, been justified by measurements made by *Tscherning* and others, inasmuch as these measurements show that the anterior surface presents its least curvature near the axis (when the eye is in relaxation), and that the posterior surface has its *greatest* curvature near the axis with a slight diminution at the periphery.

The average axial distance of the anterior surface of the cornea from the anterior surface of the crystalline lens is 3.6 *mm,*

*These are average measurements. The anterior surface of the lens has, in the measurements which I have made, varied between 9 *mm* and 11.5 *mm* (approximately); and the radius of the posterior surface has varied between 5.5 *mm* and 7.5 *mm.* Even these extensive limits have been passed in the recorded measurements of *Helmholtz* and others.

as determined by *Helmholtz.* The thickness of the cornea being regarded as 1 *mm*, the *depth of the anterior chamber* is 2.6 *mm.*

The average thickness of the lens, according to *Helmholtz,* is 3.6 *mm;* according to *Merkel,* it is 3.7 *mm; Tscherning* gives 4.1 *mm.* The lack of agreement between these figures is doubtless due in part to the fact that, on account of the difficulty of observation, the number of individuals examined by each investigator was not large enough to establish a correct average; but it seems certain that *Helmholtz's* estimate is too low. A thickness of 4 *mm* (*Listing*) may be accepted as the standard for the normal eye.

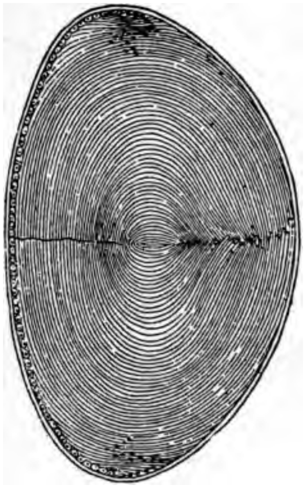


FIG. 65
Section of the Crystalline Lens (*Sernoff*).

The total or equivalent index of the lens may be derived with approximate accuracy by determining the indices of the outer, intermediate, and nuclear layers, and by calculating therefrom the refractive power of a lens composed of these layers. These determinations have been made by a number of investigators with fairly close approximation to uniformity. According to *Woinow* the average index of the adult lens is 1.4386. *Fleischer* assigns 1.4371 as the equivalent index, which was adopted by *Helmholtz* in his later schematic eye. A more recent estimation by *Stadfelt* assigns 1.435 as the equivalent index.

Listing (and Helmholtz in his first schematic eye) adopted

the fraction $\frac{16}{11}$ (1.4545) as the index of the lens. That this is too high is evidenced by the insufficient length (22.2 *mm*) of *Listing's* schematic eye.

Tscherning adopts 1.42, which, on the other hand, is apparently too low, since the length of the eye as determined by calculation with this index is longer than the emmetropic eye as measured by anatomists.

For the purpose of calculation an index of 1.437 may be accepted as the average for the normal eye. Assigning this index to the lens, and 1.337 as the index of the aqueous and vitreous, we determine from calculation that the crystalline lens (*in situ*) has a focal length of about 51 *mm*. If we could disregard the thickness of the lens this focal length would correspond to a dioptric power of 19.5 D; but that we cannot without error disregard the thickness is apparent from the application of the formula for conjugate foci. We find that a lens of about 14.5 D, placed at the anterior surface of the crystalline lens, would, in conjunction with the corneal refraction, bring parallel rays to a focus on the imaginary retina of the schematic eye. If, on the other hand, the imaginary thin lens is placed at the posterior surface of the crystalline lens, it must have a power of about 21.5 D. If we place the lens 2 *mm* behind the anterior surface of the crystalline lens—between its two nodal points—the required power is about 17.5 D, which we may, with as near an approximation to accuracy as is possible, regard as the dioptric equivalent of the normal crystalline lens.

The crystalline lens, composed of fibers (Fig. 65), is divisible into three principal segments, and it not infrequently happens that in a healthy eye the indices of these separate segments are not quite uniform. From this there results a condition of *irregular astigmia*—a defect which, in fact, exists to some extent in all eyes.

The transparency of the lens is rendered imperfect by its heterogeneity of structure. Reflection from the interfibrillar substance and from the lines of union of the segments of the lens can, under favorable circumstances, be observed in the examination of an eye.

We may observe the shadows (*the lens-spectrum*) which defects of transparency cause to fall upon our own retinas. We may do this most readily by admitting to the eye, in a dark room,

a beam of light which is diffused upon the retina by a strong convex or concave lens (15 D) placed as near as possible to the eye, as in a trial frame. The light from a lamp may be reflected into the eye by the surface of another strong lens obliquely inclined (*Norris*), or by the ordinary concave forehead mirror. The examination of the lens-spectrum shows numerous opacities which would not otherwise be suspected (Fig. 66).

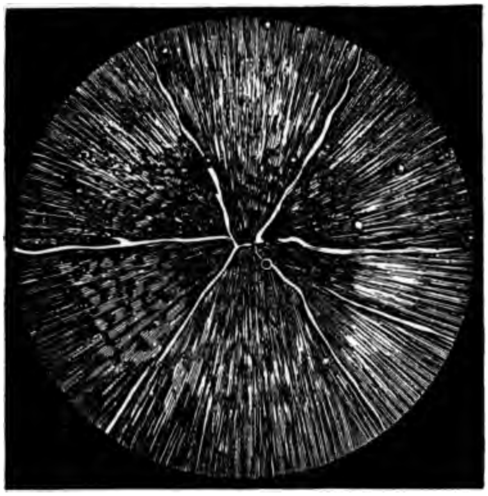


FIG. 66
Lens Spectrum. (*Donders.*)

The lens becomes less transparent in old age, and sometimes assumes a yellowish hue. This physiological loss of transparency does not materially interfere with vision, but in a certain proportion of cases a still further change occurs—an infiltration between the fibers—whereby the lens loses its transparency and becomes cataractous.

In old age there is usually an increasing density of the cortex, which makes the whole lens approach homogeneity, the effect being a diminution of the refracting power of the lens. On the other hand, a pathological swelling of the nucleus which is frequently the precursor of cataract, may increase the refractive power and produce myopia.

The vitreous body fills the greater part of the cavity of the eyeball—all that part which is back of the crystalline lens.

The refractive index of the vitreous is determined in the same way as is that of the aqueous. All estimates agree in assigning indices so nearly identical for these two media that they may be regarded as identical for the purpose of calculation.

The transparency of the vitreous body seems perfect when examined in the normal eye with the ophthalmoscope, but by looking at a uniformly bright light, as the sky, it is possible to see shadows which opacities in this substance cast upon our own retinas. These opacities are due to connective tissue cells and leucocytes which float in the vitreous. They are called *muscae volitantes,* because they appear as flies flitting before the face. They do not interfere with vision except when in disease a pathological multiplication of these cells takes place.

Insensitiveness of the Periphery of the Retina.—In refraction by a series of surfaces it is only in the vicinity of the primary optic axis that well defined images are formed. The insensitiveness of the peripheral portions of the retina is a provision of nature which prevents our noticing the diffused condition of the images as they are formed at a considerable distance from the optic axis. Although the field of vision in a healthy eye is large, it is within a very small part of this field that a clear visual impression of an external object is received. If an object lying within this field of indistinct vision attracts attention, the eye is at once turned by its muscular apparatus into the proper position to receive a clear image.

The fovea centralis, upon which falls the image of every object attracting the visual attention, does not exceed 0.4 *mm* in diameter.

We see, therefore, that that part of the retinal image which is utilized in distinct vision is extremely small; and we must not think that vision is properly represented by the diagrams which we often see having the image pictured as covering a large part of the retina. We see the various parts of an object by rapidly changing the visual attention from one part to another. The eye is constantly in motion, bringing the image, first of one part of the object and then of another upon the fovea.

Alpha and Gamma.—If the eye is a well constructed optical apparatus, the fovea centralis must lie at or near the intersection of the axis and the retina. As a matter of fact the fovea

always lies near the axis, but seldom upon it. It is apparent therefore that the nodal ray which joins the fovea with the point looked at does not coincide with the primary axis of the eye.

This is shown in an exaggerated degree in Fig. 67, in which *F F'* is the optic axis and *V V'* is the nodal ray joining the fovea and the point to which the visual attention is directed. The point *V* is called the point of fixation, and the line *V V'* is called the *visual line.*

The angle which the visual line makes at the nodal point with the optic axis is the angle *alpha* (α) of *Donders.* This angle varies considerably in different persons. As a rule the fovea

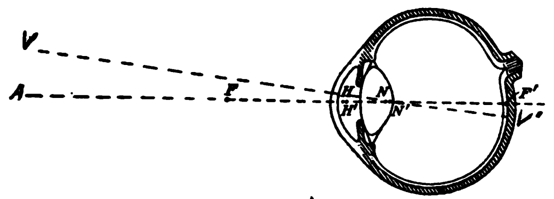


FIG. 67

Angle Alpha—Alpha is represented by *A N V*, or by *F' N' V'*.

(*V'*) lies farther from the optic disk than the focus (*F'*), and consequently the visual line intersects the cornea on the nasal side of the optic axis. This is called the *positive angle alpha.* When, as less frequently happens, the visual line intersects the cornea on the temporal side, alpha is said to be *negative.* In the horizontal meridian alpha is usually not more than five degrees in conditions approximating emmetropia. In the vertical meridian it is seldom more than two or three degrees, the visual line lying above the optic axis.

Alpha is greatest in hyperopia, and least in myopia. In the latter condition alpha is sometimes negative. *Donders* gives seven and one-half degrees as the average of this angle in the higher degrees of hyperopia. Very rarely it may reach ten degrees.

To measure the angle alpha we place the electric lamps of the ophthalmometer in the meridian at right angles to that in which we wish to determine the angular displacement of the lens. We then note the angle which the visual line makes with the axis of the telescope when the images reflected from the anterior surface of the cornea and from the two surfaces of the crystalline

lens are in alignment. In order that the images reflected from the two surfaces of the lens may be seen simultaneously an instrument of long focal length is required, such as *Tscherning's* ophthalmo-phakometer.

Sometimes it will be found impossible to bring all three images into alignment. In such cases there is a defect of centering; the three surfaces have no common axis. Absolute exactness is not to be expected, but ordinarily the deviation from a correct centering is slight.

Although the images from all three surfaces cannot be seen simultaneously with an instrument of short focal length, we can measure with such an instrument the angle alpha with sufficient accuracy for practical purposes by bringing into alignment the images as reflected from the cornea and from the posterior surface of the lens.

The angle which *Donders* called alpha has been called gamma (γ) by *Landolt,* who has characterized as alpha the angle which the imaginary long axis of the corneal ellipse makes with the visual line. The measurements of *Tscherning* and others have shown that the summit of corneal curvature seldom lies at a noteworthy distance from the optic axis; practically therefore the angles *alpha* and *gamma* of *Landolt* may be regarded as identical, and either of them may be regarded as expressing the angular distance between the visual line and the optic axis.

The Iris.—The iris has already been described as an adjustable diaphragm which is placed just in front of the anterior surface of the lens. *The pupil,* through which light passes to the retina, is at or near the center of the iris, usually slightly to the nasal side. The peripheral rays of light which are most affected by the optical imperfections of the eye, are thus prevented from reaching the retina.

The size of the pupil is regulated by the sphincter and dilator muscles of the iris. Stimulation of the retina by a bright light produces by reflex action a contraction of the pupil. When this stimulus is removed during feeble illumination the pupil dilates so as to permit more light to enter the eye.

The pupil also contracts consensually with accommodation and convergence.

The apparent size of the pupil as we see it is somewhat larger than the actual size, since it is magnified by refraction as the rays from its border leave the cornea. Its diameter appears about one-eighth larger than it really is.

We cannot fix any definite size of the normal pupil, since this varies with the degree of illumination, and also with different individuals under the same conditions. The pupil is larger in early life and becomes notably smaller in old age. The average diameter of the pupil in ordinary daylight is usually regarded as being about 4 *mm.*

Choroidal and Retinal Pigment.—The inner surface of a photographic camera is blackened for the purpose of absorbing all extraneous light. In the eye the pigment of the choroid and retina performs this function, thus preventing internal reflections with consequent marring of images.

REFRACTION OF THE EYE

The refraction of the eye is the expression which we use in ophthalmology to indicate the relation between the position of the retina and the posterior principal focus of the dioptric system of the eye.

The *static* refraction expresses this relation as it exists during complete relaxation of the ciliary muscle. By the term *dynamic* refraction we express the power of increasing the refractive action which the eye possesses in the accommodative contraction of the ciliary muscle. When the term *refraction of the eye* is used without qualification it refers to the *static* refraction.

Emmetropia.—When the principal focus lies at the intersection of the optic axis and retina during relaxation of the ciliary muscle, the eye is adapted to receive a clear image of a distant object. This is the ideal eye. It is regarded as the normal type of the human eye, and it is called the emmetropic eye.*

Nature approximates but seldom attains emmetropia, and it is evident that the more the methods of measurement are refined the less will be the proportion of eyes regarded as

* The word "emmetropia" was derived by Donders from the Greek ἔμμετρος (in due measure) and ὤψ (eye or vision).

emmetropic. We must therefore assign limits within which the emmetropic eye may vary. These limits are determined practically by the weakest lenses (plus and minus) in the complete trial case. We regard an eye as emmetropic when the weakest lens of the trial case does not bring the retina and focus into greater proximity than they are without the lens.

Axial Length of the Emmetropic Eye.—It is not within the range of probabilities that individaul normal eyes should present uniformity either of curvature or of axial length; but, as the researches of *Helmholtz* and others show that the curvature varies only within comparatively small limits, so also anatomical examination of eyes which were known to be emmetropic, or nearly so, shows that their axial length varies to a correspondingly slight extent.

The distance from the anterior surface of the cornea to the retina, as determined by my calculation, is 23.22 *mm.* The thickness of the choroid and sclera in the region of the macula is about 1 *mm;* theoretically, therefore, the antero-posterior diameter of the normal eye should be 24.22 *mm* in length. That it does not in fact deviate much from this average is attested by anatomists, who find the length of the normal eye to vary between 23 *mm* and 25 *mm.* *Merkel* assigns 24.3 *mm* as the average length; *Sappey* (average of 28 eyes of both sexes), 24.2 *mm; Macalester's Anatomy* (1889), 24.27 *mm; Morris's Anatomy* (1894), 24.5 *mm,* and *Quain's Anatomy* (1894), 24 *mm.*

These measurements apply to the eyes of adults. The eyes of infants and young children are notably smaller than the eyes of grown persons. Although the smallness of the eyes in childhood is a physiological condition, such eyes are usually hyperopic, and their consideration belongs to the chapter devoted to that condition.

Accommodation

In emmetrop'a the macula lutea coincides with the posterior principal focal plane of the eye, and the eye, if otherwise normal, fulfils the conditions necessary to receive a clear image of a distant object. But the image of a near object would be formed at its conjugate focal plane, behind the posterior principal focal plane, and since light would be intercepted by the retina before reaching this conjugate focal plane, the rays from any point of

the object, not having reached their intersecting point, would form upon the retina a diffusion-circle. The image of the object, being an aggregation of such diffusion-circles, would be blurred.

In order to overcome the indistinctness of vision which would result from these diffusion images, we make use of the power of accommodation, as far as this is available.

The mechanism of accommodation, the means by which we are enabled to adapt the eye for different distances, has engaged the attention of physicists for more than three hundred years; it has been the subject of many writings and of much contention. The celebrated astronomer *Kepler,* who was the pioneer student of the dioptrics of the eye (1611), sought to account for the power of accommodation by postulating a change in the length of the eye—a change which he thought might be accomplished by muscular compression.*

Scheiner (1619) described the pupillary contraction which occurs in accommodation, and suggested that changes might also occur in the crystalline lens, but *Des-Cartes* (1637) is usually regarded as the originator of the idea of an increase of convexity of this lens.

The first definite proof that accommodation is due to an increase of convexity of the crystalline lens was given by *Young* (1801). There were three credible hypotheses for the explanation of accommodative action: (*a*) that it was accomplished by *increase of curvature of the cornea;* (*b*) *by increase of curvature of the crystalline lens;* and (*c*) *by elongation of the eyeball.*

Young proved (1) that there was no increase of curvature of the cornea during accommodation and (2) that the eyeball was not elongated. He proved the first proposition by observing the images reflected from the cornea, and also by immersing his eye in water in such a way that the refractive action of the cornea was eliminated and replaced by a convex spherical lens. In order to prove that there was no elongation of the eyeball he took advantage of the fact that he had very prominent eyes. By turning the eye as far as possible inward, and by inserting a small ring between the bone and the posterior polar region

*The statement made by *Helmholtz* and subsequent writers that *Kepler* believed accommodation to be accomplished by a to-and-fro movement of the crystalline lens is erroneous.

of the eye he proved that his accommodative power was unaffected, although it was impossible for the eye to elongate.

Young also proved by means of his optometer that persons who had been operated on for cataract had no power of accommodation. He therefore firmly established that this power resided in the crystalline lens, and therefore that it could only result from an increase in the curvature of this lens.

As the nature of the ciliary muscle was at that time not known, *Young* was unable to give a rational explanation of the means by which the change of curvature was accomplished.

It is said that *Young's* work attracted but little attention at the time and that it was only after the renewed study of this subject nearly fifty years later that his experiments were accredited.

The fact that accommodation is accomplished by an increase of curvature of the crystalline lens was first actually demonstrated by *Langenbeck* in 1849, who observed the changes in the images formed by reflection at the anterior surface of the lens. A little later (in 1851) *Cramer* constructed a magnifying instrument with which he could better observe these images, and he was able to demonstrate very clearly the movement of the images which occurred in accommodation. Finally *Helmholtz* by the invention and application of his ophthalmometer was enabled to measure the size of the image as formed at the posterior as well as that at the anterior surface of the lens. He was therefore able to measure the amount of increase of curvature which took place. He observed that while by far the greater part of the accommodation was due to the increased curvature of the anterior surface, there was also a slight change of curvature of the posterior surface.

From his investigations *Helmholtz* concluded that, 10 *mm* being the average radius of curvature of the anterior surface of the crystalline lens during relaxation, 6 *mm* is the average radius during maximum accommodation in young adults; that the radius of the posterior surface of the crystalline lens changes from an average of 6 *mm* to an average of 5.5 *mm;* and that the thickness of the lens increases from 3.6 *mm* to 4 *mm,* with a corresponding advance of the anterior surface. These conclusions of *Helmholtz* have been universally accepted, as regards all but

the increased thickness of the lens, which *Tscherning* thinks has not been definitely proved.

The Ciliary Region.—The lens, whose general form and size have already been described, is fibrillar in structure and varies in consistency according to the age of the individual. In infancy the entire lens-substance is of a soft semifluid or gelatinous nature; but with increasing age the central or nuclear portion gradually becomes firmer in consistency. By the time adult life is reached the nucleus has become weakly solidified. This hardening process continues so that the nucleus increases in size and hardness as the maturity of the individual advances. The outer or cortical portion also increases in firmness, and in old age the entire lens is transformed into a solid mass, with a nucleus of still greater hardness.

The lens substance is enclosed in a delicate, transparent, and contractile capsule.

The lens, enclosed in its capsule, is supported in its position between the iris and aqueous humor on one side and the vitreous body on the other by a delicate ligament—the *zonule of Zinn,* or *suspensory ligament* of the lens. This ligament is attached to the anterior and posterior surfaces of the capsule near the equator or peripheral border of the lens (Fig. 61).

The ligament, thus attached to the lens, has its outer border attached to the ciliary processes and to the depressions between these processes. Opposite to the equator of the lens, about .5 *mm* distant and projecting anteriorly, lie the ciliary processes, a network of blood vessels and pigment which line the inner circumference of the sclero-corneal ring, and which, extending backward, become united with the choroid.

The muscular character of the ciliary body was discovered by *Wallace,* an American physician, in 1836. As American literature was at that time little known in Europe, *Wallace's* discovery received practically no attention, and later *Bowman* in England and *Brücke* in Germany described the muscle at about the same time (1847).

The ciliary muscle lies beneath the ciliary processes. It is composed of non-striated fibers and consists of two parts. The larger portion is formed of meridional fibers, usually called *Brücke's muscle,* which are attached anteriorly with firm union to the sclero-corneal junction and neighboring part of the sclera.

The fibers of this part of the muscle, passing backward, are inserted into the anterior portion of the choroid. This is the most external part of the muscle, its outer surface being in contact with the sclera. On the inner side of the meridional fibers and adjoining the ciliary processes is the second or transverse part of the muscle, ordinarily known as the *annular muscle of Müller.* This consists of a circular band of fibers surrounding the margin of the iris. Some of the fibers, after proceeding for a certain distance transversely, penetrate this part of the muscle and join the first or meridional portion.

In emmetropia the proportion in size of the two divisions of the muscle is about ten of the first to one of the second; while in hyperopia the circular portion is more abundant, and in myopia it is less so or even absent (*Iwanoff*).

The sphincter of the iris and the ciliary muscle are innervated by the third nerve, acting through the ciliary ganglion. These muscles are therefore involuntary in their action; contraction occurs as the result of reflex stimulation. We have no control over the pupillary movements, but to a certain extent we can cultivate the power of voluntarily contracting and relaxing the ciliary muscle.

Helmholtz's Theory.—It was *Helmholtz* also who, after demonstrating the changes which occur in the lens during accommodation, first presented a rational explanation of the way in which these changes are accomplished. He assumed that, the anterior extremity of the ciliary muscle being attached to the firm sclero-corneal junction, contraction of this muscle would draw forward the anterior portion of the choroid, to which the posterior extremity is attached. In consequence of this forward motion the ciliary processes and the suspensory ligament of the lens would also be drawn forward, and relaxation of this ligament would occur.

If we assume, with Helmholtz, that this relaxation and forward movement actually occur, we need only to glance at our illustration (Fig. 68), and to bear in mind the constitution of the lens in order to understand what will, in a general way, be the effect of this relaxation upon the shape and position of the lens.

In childhood, at which period accommodation is most active,

the lens consists of a semifluid or gelatinous mass enclosed in a contractile capsule. The tendency of such a mass is to ***approximate*** the spherical form. This is because a fixed volume of matter presents its smallest area of external surface when in this form, and what is known in physics as the *surface-tension*

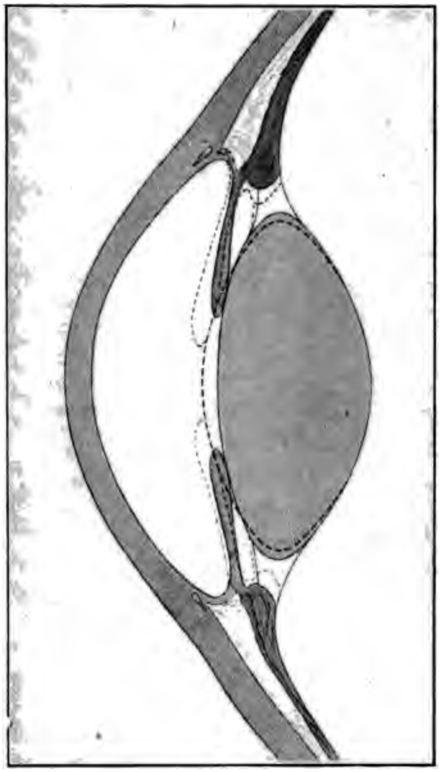


FIG. 68

The crystalline lens and ciliary region. The dotted outline represents the change which occurs in accommodation.

of the mass and also the contractility of the capsule are ever acting to reduce this surface-area. A simple illustration of this is afforded by a thin rubber bag distended with water. If by pressure or traction on the bag the shape is altered, its original form will at once be resumed on release from pressure.

Although the tendency of such a body is to assume the spherical form, there may be a number of counterbalancing forces which prevent this form from being attained. In the case of the rubber bag, for instance, the structure of the latter may be such as to give an oval form to the body. Similarly, in the lens there are modifying conditions, resulting from its characteristic structure, and even if no external traction were exercised, a perfectly spherical fonn would not be assumed.

In its normal position in the eye the pressure or traction by the suspensory ligament causes the lens to assume an ovoidal form. We observe that the anterior part of this ligament is shorter than the part which is attached to the posterior surface of the lens, and that, as a result of this, the tension is greater upon the anterior than upon the posterior surface. As the tension is greater upon the anterior surface, so the effect of relaxation must be greater upon this than upon the posterior surface. Hence, if the lens has not become solidified in its flattened form, relaxation of the ligament allows the anterior surface to advance with a decided increase of curvature. The effect of relaxation of the posterior portion of the ligament being less marked, the posterior surface undergoes only slight increase of curvature with no measurable change of position.

Experimental Observations.—The first experimental observations made for the purpose of ascertaining whether the changes which take place in accommodation agree with the assumption of *Helmholtz* were undertaken by *Hensen and Voelckers*. Their experiments, which were made upon the lower animals, consisted in exposing the ciliary ganglion and ciliary region, and observing the changes caused by irritation of the ciliary nerves. By this means they were able to demonstrate: (1) contraction of the pupil with a forward motion of the pupillary border of the iris, and of the anterior surface of the lens, with an increase of curvature of this surface; (2) contraction of the ciliary muscle with advancement of the ciliary processes and anterior portion of the choroid.

The changes which occur in the living human eye in accommodation were investigated by *Coccius* (1867) and later by *Hjort*. *Coccius* observed eyes upon which peripheral iridectomies had been performed, and *Hjort* made use of a person in whom there existed total aniridia, the result of accident. The changes

which these investigators were able to detect resembled those which have been described by *Hensen* and *Voelckers* as occurring in lower animals. *Coccius* and *Hjort* were further enabled to view the ciliary region directly and to demonstrate that the ciliary processes advance during accommodation. Since, as these processes advance, they also become more prominent, the investigators were led to believe that the efferent veins from this region were compressed, and that, in consequence, there was an increase of intra-ocular pressure. Subsequent investigations, however, have shown that there is no such increase of pressure during accommodation.

Resting upon these demonstrations, *Helmholtz's* theory of accommodation has received almost universal acceptance, but its correctness has been denied by several able investigators.

Tscherning's Theory.—*Tscherning*, who is the chief advocate of the counter-theory that accommodation is produced, not by relaxation but by increased tension of the suspensory ligament, gives the following reasons for rejecting *Helmholtz's* theory:

"(1) The increase of refraction of the lens in accommodation takes place only near the apex of the lens. This is established by study of the spherical aberration of the eye. Aberration, which is positive when the eye is at rest, diminishes or even becomes negative in maximum accommodation.

"(2) Measurements with the ophthalmo-phakometer show that the increase of curvature of the anterior surface of the lens is confined to the portion near the summit of the lens, and that the *anterior surface does not move forward,* but remains stationary or moves slightly backward.

"(3) Experiments made upon the eyes of animals show that traction upon the ligament of the lens produces an increase of curvature near the summits of the surfaces, and relaxation produces diminution of curvature."

Helmholtz confined his measurements to the portion of the surfaces near the optic axis, but *Tscherning* has investigated the curvature of more peripheral parts of the lens-surfaces. He has found that the curvature of the anterior surface, which plays the more important part in accommodation, diminishes very rapidly as the distance from the axis increases, and he concludes that the anterior surface of the lens assumes in accommodation

a form closely approximating a hyperboloid, a form which he believes inconsistent with *Helmholtz's* theory.

The researches of *Tscherning* make it necessary for us to modify our conception of the change which takes place in the crystalline lens in accommodation, but they do not require us

a FIG. 69 *b*

Lens of a Calf.

(*a*) Under relaxation of the suspensory ligament; (*b*) Under traction of the ligament.

to abandon the theory of *Helmholtz* that the increase of curvature results from a relaxation of the zonula of the lens.* It is far easier, in my opinion, to reconcile the form of curvature as *Tscherning* finds it with *Helmholtz's* theory than it is to believe that this change can be produced by traction of the zonula.

a FIG. 70 *b*

Lens of an Ox

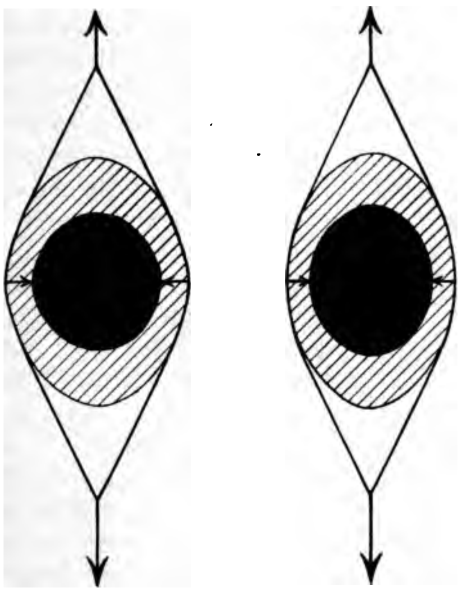
(*a*) Under relaxation; (*b*) Under traction of the ligament.

Some years ago I repeated *Tscherning's* experiments, using lenses of the calf as well as of the mature ox.† When using the lenses of the young animal I was not in any case able to obtain an increase of curvature by traction (Fig. 69). In the case of

*In fact it is apparent from *Helmholtz's* illustrations that he did not assume the existence of the spheroidal curvature of the lens in accommodation. This misconception arose in subsequent descriptions.

† Theory of Accom., Arch. of Ophth. XXIX.

the ox, however, I found that the lenses were composed of a center or nucleus of great hardness surrounded by soft material. By making traction on lenses of this kind I obtained an increase of curvature (Fig. 70). It is easy to understand why this results with the hard nucleus, but this nucleus, upon which *Tscherning's* theory is based, does not exist in childhood, the age of greatest accommodative activity. Furthermore, even if we should concede that the lens might assume the accommodation form under trac-



a FIG. 71 *b*

tion of the zonular ligament (Fig. 71, *a*), we should still find difficulty in believing that this form could be continuously maintained in the soft lens of a young person. The prolonged traction of the ligament would, after a time varying with the hardness of the nucleus produce a flattening of the latter with a diminution of the total curvature (Fig. 71, *b*).

Another matter upon which *Tscherning* lays great stress has little weight in support of his argument. He says that if *Helmholtz's* theory is correct we ought to find the lenses of dead persons in a state of maximum curvature when we remove the lenses from their attachments. We should not, however, expect

this, for with the loss of the body heat the lenses become hard and do not readily undergo a change of shape.

For anatomical information in regard to the accommodation curvature of the human lens we must depend upon eyes enucleated from living persons, and it is not often that we have an opportunity of examining normal lenses in this way. I have had this opportunity only once. In that instance I examined at the moment of enucleation of the eye a healthy lens of a man twenty-five years of age. When I removed the lens from the eye I observed that the usual flattened aspect of the anterior surface was absent; in fact the shape of this surface very closely resembled the accommodation form described by *Tscherning.* Moreover, traction made at opposite points of the equator produced a decided flattening of curvature, which disappeared on release from traction. *The action of the lens did not in any way justify a belief in Tscherning's theory.* Finally, a gentle massaging of the lens (in its capsule) between the fingers, which destroyed its characteristic structure, resulted in the lens assuming a spherical shape when released from pressure.

The foremost antagonist of *Tscherning's* theory is *Hess,* who has conducted experiments to prove that the suspensory ligament is in a relaxed condition during accommodation. The experiments of *Hess* consisted chiefly in demonstrating: (1) the correctness of the observations of *Coccius* and *Hjort;* (2) a sinking of the lens from gravity when the eye makes a maximum effort of accommodation; and (3) a change of position of the lens during accommodation with change of position of the head; that is, a forward motion with the head inclined forward (downward) and a backward motion with the head thrown back.

A brief but very clear description of these experiments, as given by Professor Hess himself in an address before the American Medical Association, may be found in the reports of the Ophthalmological Section for the year 1907.

In view of these facts and notwithstanding the plausible and ably presented arguments of *Tscherning,* I believe that we should hold to *Helmholtz's* theory of a relaxed zonula, unless this theory should be rendered untenable by more conclusive evidence than has hitherto been adduced against it.

Length of Time Required for Accommodation.— Experiments have been conducted for the purpose of ascertain-

ing how long a period of time is required for the production and relaxation of accommodation. As a result of these experiments it is stated that it requires from one to two seconds to change the adaptation from the distance adjustment to the usual reading position, and about one-half of this period to produce the inverse change. The length of time required for these acts varies in different persons and at different ages, a greater time being required as the crystalline lens becomes more solid in consistency.

Range of Accommodation.—Since the solidity of the lens undergoes a gradual increase from infancy to old age, it follows that the power of this lens to assume greater convexity under the relaxing influence of the ciliary muscle must suffer a gradual diminution with advancing years. At ten years of age, the youngest period of life at which accommodation can well be measured, the normal eye can accommodate for a point about 70 *mm* from the eye; at twenty years of age the nearest point for which the eye can accommodate is 100 *mm;* at forty-five years the nearest point is about 250 *mm;* and at seventy years little or no accommodative power ordinarily remains.

The nearest point for which an eye can accommodate is called the *near point* (*punctum proximum, p. p.*).

The dioptric equivalent of the accommodative power of an eye is called the *amplitude* or *range of accommodation.*

The following table gives *Donders's* estimate of the range of accommodation of the eye at different ages.

Age	10	15	20	25	30	35	40	45	50	55	60	65	70	75
Diopters*	14	12	10	8.5	7	5.5	4.5	3.5	2.5	1.75	1	0.75	0.25	0

While the range of accommodation is the same in ametropia (except in high degrees) as in emmetropia, the position of the near-point varies with the state of refraction. Thus, in an emmetropic eye which has 4 D of accommodation the far-point is at infinity and the near-point is at a distance of one-fourth of a meter from the eye. In the case of a hyperopic eye a certain amount of accommodation must be exercised to procure distinct distant vision, and only what remains is available for near vision. If in an eye having 4 D of accommodation there is hyperopia of 2 D, only 2 D will remain for adapting the eye to near vision, and the near-point is one-half of a meter from the eye.

*Adapted from the inch system by Landolt.

The far-point of the hyperopic eye is negative—that is, only convergent pencils can be focused on the retina without accommodation; but as no convergent pencils enter the eye (except by previous refraction), the negative part of the range of vision is of no use in ordinary vision, and practically the far-point of the hyperopic eye lies at infinity. Hence, in the aforementioned case the range of vision is from infinity to a point one-half of a meter from the eye.

If, on the other hand, there is myopia of 2 D, the far-point lies at a distance of one-half of a meter from the eye. Beyond this point distinct vision is not possible; but for near vision, if this eye can command 4 D of accommodation in addition to the 2 D of myopia, its lens-equivalent is in all 6 D. The near-point of distinct vision is, therefore, one-sixth of a meter from the eye, and the range of vision embraces only the interval lying between these two points, distant, respectively, 500 *mm* and 167 *mm* from the eye.

The emmetropic eye requires 4 D of accommodation to see distinctly at a distance of one-fourth of a meter; the eye having 2 D of hyperopia requires 6 D; and the eye having 2 D of myopia requires 2 D of accommodation for vision at this distance.

It will be noticed that while 1 D of accommodation will change the adaptation of the eye from infinity to a point one meter from the eye, an additional diopter will effect a change from one meter to one-half of a meter only, and another addition of one diopter will change the adjustment from a point one-half of a meter distant to a point one-third of a meter from the eye. Thus we see that as an object approaches the eye the amount of accommodation required for distinct vision increases at a rapidly increasing rate.

Reserve Accommodation.—It is not possible for anyone to use all his accommodative power for a prolonged period of time. Investigations by *Landolt* have shown that about one-third of this power must be held in reserve, if continuous work is to be done. A person having just 3 D of accommodative power could not read continuously at 33 *cm;* in order for him to do this he must have at least 4.5 D at his disposal, for he must keep in reserve 1.5 D (1/3 of 4.5 D), leaving 3 D for actual use.

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CHAPTER IX

THE MOTOR MECHANISM

The eyeball is much smaller than the cone-shaped cavity of the orbit in which it is lodged. The space between the eye and the bony wall of the orbit is filled with muscles, fascia, cellular, and adipose tissue. The muscles form a cone similar in shape to the cone of the orbit, but smaller. In the hollow of this cone the eye is embedded, the fascia, cellular, and adipose tissue filling up the rest of the orbital cavity.

The fascia of the orbit is well adapted for retaining the eye in its proper position and at the same time allowing freedom of motion about its center.

The fibrous sheath which surrounds the eyeball was first accurately described by *Tenon* (1806), from whom it takes its name. This fascia extends from the lids and periosteum anteriorly, and, investing closely the eyeball, extends posteriorly along the optic nerve to be blended with the periosteum at the apex of the orbit. It also envelops the ocular insertions of the recti muscles and continues over from one muscle to another, so as to form a circular band of fibrous tissue and muscular tendons. Strong ligamentous bands are stretched between the eyeball and the periosteum of the orbit.

This fascia is sometimes called *Bonnet's capsule* from a later anatomist who described it (1841), and who called attention to the intimate adherence of the fascia to the muscular tendons. It is because of this adherence that we can sever the tendon for the correction of strabismus without entailing serious impairment of action of the muscle.

More recently the orbital fascia has been the subject of study and description by *Motais,* whose plates have been made use of in almost all recent text-books dealing with the ocular muscles.

Some of these plates are made with a special view to showing the *check ligaments,* the strong prolongations of fascia

which extend between the eyeball and the anterior part of the orbit (Fig. 72). These ligaments have an important use in limiting the rotations of the eye and in keeping it in its proper position in the orbit.

The Extrinsic Muscles of the Eye.—There are attached to the eyeball for the purpose of controlling its movements six muscles, *four recti* and *two oblique* (Fig. 73). These six

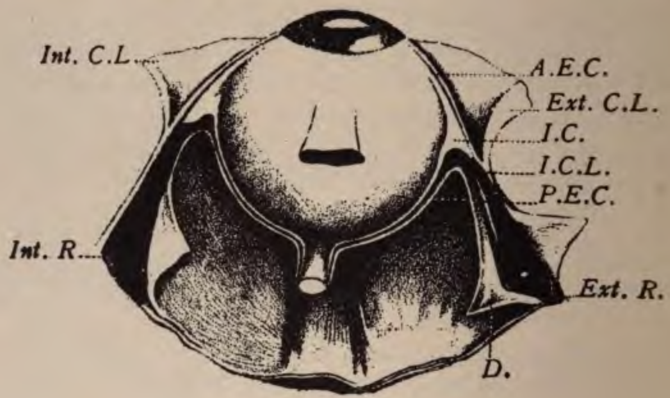

FIG. 72

Tenon's Fascia (from *Motais*). *Int. C. L.* and *Ext. C. L.*—Internal and External Check Ligaments. *Int. R.* and *Ext. R.*—Internal and External Recti. *A. E. C.* and *P. E. C.*—Anterior and Posterior External Capsule. *I. C. L.*—Intra-capsular Ligament, or "Collarette." *I. C.*—Internal Capsule. *D.*—Deep Layer of Muscular Sheath.

muscles are called *extrinsic* or extra-ocular muscles in contradistinction to the ciliary and iritic muscles, which are the *intrinsic* muscles of the eye.

The four recti muscles arise from the margin of the optic foramen, and in their course forward bound the funnel-shaped space in the hollow of the basal portion of which the eyeball rests.

The internal rectus is attached anteriorly to the sclera on the nasal side of the eye, about 5 *mm* from the margin of the cornea.

The inferior rectus is similarly attached at the lower side of the sclera, about 6 *mm* from the margin of the cornea.

The external rectus is attached at the temporal side, about 7 *mm* from the margin of the cornea.

The superior rectus is attached above, about 8 *mm* from the margin of the cornea.

These are average measurements as determined by *Motais*. They may be easily remembered, since they correspond to the consecutive numbers, 5, 6, 7, 8. In the case of the superior and inferior recti, whose lines of insertion are obliquely inclined to the corneal margin, the measurements refer to the middle points of the attachments.

The insertions of the recti muscles have been diagrammatically represented by *Fuchs* (Fig. 74). His measurements differ slightly but not materially from those of *Motais*.

The internal rectus is most favorably attached for rotating the eye, and the inferior rectus holds the second place in this respect. This is in accordance with the physiological requirements, since the greatest tax is imposed upon these two muscles.

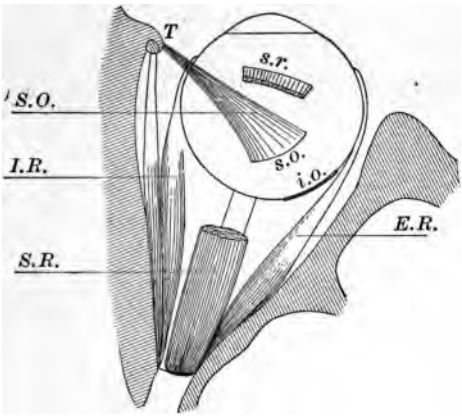

FIG. 73

Showing the origin and attachment of the extra-ocular muscles and the position of the eyeball in the orbit. The letter *T* represents the trochlea, which is at the inner and upper angle of the orbit; *E. R.* represents the external rectus, *I. R.* the internal, and *S. R.* the superior rectus; *S. O.* represents the superior oblique. The inferior rectus and the inferior oblique are not shown. The scleral attachment of the superior rectus is represented by *s. r.*, that of the superior oblique by *s. o.*, and that of the inferior oblique by *i. o.* (After *Fuchs*.)

The breadth of the tendons at their lines of insertion is from 10 *mm* to 11 *mm*, except for the inferior rectus, the breadth of which is somewhat less, from 9 *mm* to 10 *mm*.

Nerve Supply of the Extrinsic Muscles.—*The third or oculomotor nerve* supplies all the extrinsic muscles of the eye except the superior oblique and the external rectus. *The superior*

oblique is supplied by the *fourth,* and the *external rectus* by the *sixth* nerve.

Ocular Motions.—The eyeball is freely movable in all directions. *The primary position* is defined as that position which

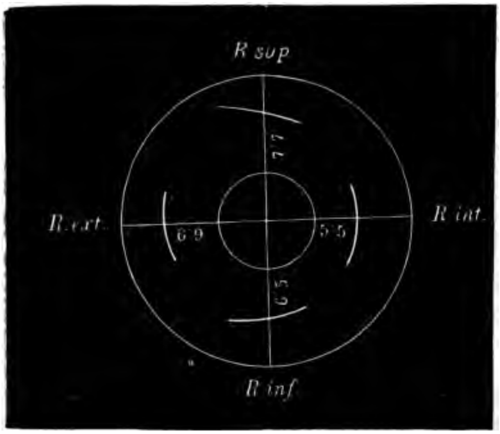

FIG. 74

Diagram showing scleral attachments of the ocular muscles. (*Fuchs.*)

the eye occupies when, with head erect, the visual attention is directed straight forward at the horizon.

When the cornea is turned nasalward the eye is said to be *adducted;* when the cornea is turned temporalward the eye is *abducted.* Similarly upward rotation is called *supraduction* or *elevation;* downward rotation is *subduction* or *depression.*

In place of these terms we may use *adversion, abversion, supraversion,* and *infraversion.*

When the eye rotates around its antero-posterior axis, or when the normally vertical meridian loses its verticality the eye is said to undergo *torsion.* When the upper margin of the cornea is rotated temporalward the torsion is called *positive* (also called *extorsion*); when the upper margin of the cornea is rotated nasalward the torsion is *negative* (*intorsion*).

The internal and the external recti muscles form a pair; both rotate the eye around its vertical axis.* The internal muscle

*In referring to the action of the ocular muscles we mean, in general, the action which would be exerted when the eye is in the primary position.

draws the cornea inward, or produces *adduction;* while the external muscle draws the cornea outward, or produces *abduction.*

The superior and inferior recti do not form a pair of muscles acting in the same plane, as do the internal and external recti. This is because of the divergence of the orbits. When the eye is in the *primary position,* contraction of the superior rectus will draw the cornea upward (*supraduction*), but it will also draw it inward, and will produce an inward rotation (around the antero-posterior axis) of the upper border of the cornea. If the eye has been previously adducted by contraction of the internal rectus, these subsidiary functions of the superior rectus will be increased; but if on the other hand the eye has been previously abducted by contraction of the external rectus the subsidiary actions will be diminished, and when the antero-posterior axis lies in the plane of muscular action, the superior rectus will act as a simple elevator of the cornea (Fig.

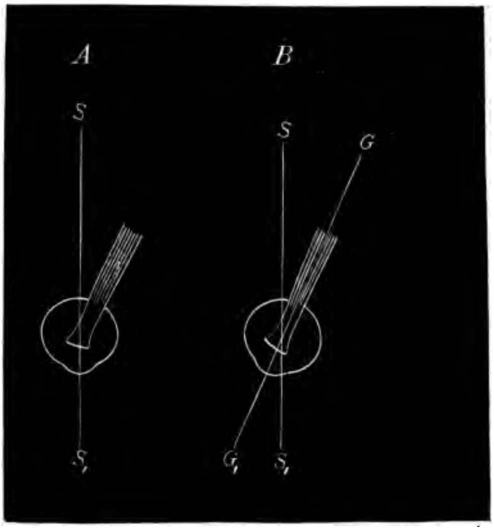

FIG. 75

Showing the effect of abduction upon the action of the *superior or inferior rectus* (*Fuchs*).

75). In still greater abduction subsidiary actions opposite to those which have been described arise.

As the chief function of the superior rectus is to draw the cornea upward, so the chief function of the inferior rectus is

to draw the cornea downward, but the subsidiary actions of the two muscles do not lie in the same plane; for when the eye is in the primary position contraction of the inferior rectus not only draws the cornea inward, but at the same time it rotates the lower margin of the cornea inward. As with the superior rectus, these subsidiary actions are greatest when the eye is adducted, and they vanish when the eye is so abducted that the antero-posterior axis lies in the plane of muscular action.

The superior and inferior recti make about the same angle with the median plane. This angle varies in different persons. The average as determined by *Fuchs* is 23°. Other authorities give a somewhat larger angle as the average, about 27°.

The superior oblique muscle draws the cornea downward and outward and at the same time it rotates the upper margin of the cornea inward. The last of these motions is greatest when the eye is in abduction, and it diminishes in adduction.

The superior oblique counteracts the subsidiary effects of the inferior rectus, so that by the combined action of these two muscles the cornea may be drawn directly downward.

The inferior oblique draws the cornea upward and outward and rotates the upper margin of the cornea outward. The last motion is greatest in abduction and least in adduction.

The inferior oblique acts in conjunction with the superior rectus and by counteracting the subsidiary effects of the latter, it permits the cornea to be drawn directly upward.

It is probable that an important function of the two oblique muscles is to counteract the backward pull of the recti muscles. The eye, being thus properly poised, rotates freely without displacement.

Center of Rotation.—It has not been absolutely demonstrated that the eye has a fixed center of rotation for all motions, but if there is a change of center it is slight. Several methods have been used to find this center. The method of *Donders and Dojer* is usually accepted as being the most reliable. In the application of their method these investigators first measured the diameter of the cornea with an ophthalmometer. They then suspended a fine hair in front of and close to the cornea, and examined the angle through which the eye turned in order to bring first one and then the other border of the cornea directly behind the hair as seen by the examiner in the telescope. From this angle and

from the diameter of the cornea they deduced the position of the center of rotation.

This method has been criticised because the position of the center of rotation is assumed in measuring the angle through which the eye turns. But as this angle is measured with a large radius, the result is not vitiated.

In accordance with their calculations we place *the center of rotation* at a point on the antero-posterior axis 13.5 *mm* behind the anterior surface of the cornea in *emmetropia. In hyperopia* the distance is slightly less, and *in myopia* it is greater than in emmetropia.

Field of Fixation.—The field of fixation measures the rotary power of the ocular muscles. The maximum rotation which the eye can make in any direction is measured by the angle included between the visual line in maximum rotation and the visual line in the primary position.

The average extent of the field of fixation in the normal eye is, according to *Landolt,* 47° in all directions. Other authorities give a higher degree of downward rotation and a somewhat less degree of upward rotation. *Stevens* assigns 30° as the upward limit and 60° as the downward limit.

The means which we use for measuring the field of fixation will be given in a subsequent chapter.

BINOCULAR FIXATION

Binocular vision is the fusion into a single perception of the two impressions transmitted to the visual areas of the brain from the two eyes. There is a slight dissimilarity between the two retinal images because of the difference in the position of the eyes.

Helmholtz has estimated that we can perceive a difference in the images, as seen monocularly, for all distances which do not exceed 240 meters. In arriving at this conclusion he based his calculations upon the experimental observation that we can discern a difference of one minute of an arc.

By means of this difference between the images, and aided by certain psychic influences, we are able to estimate distances and solidity; in other words, we visually perceive the three dimensions of space by the proper interpretation of the two dissimilar images on our retinas.

The fusion of the two images in normal binocular vision is possible only when the image of direct vision falls upon the fovea centralis of each eye. The visual lines must therefore meet at the point of fixation. The maintenance of the proper adjustment of the visual lines is made possible by a marvelous correlation of action of the various ocular muscles.

Conjugate Movements

When our attention is directed to an object which does not lie in the median plane we may fix the eyes upon the object either by turning the head or by turning the eyes or by a combination of both movements. If we are to gaze at the object for any length of time we depend upon movement of the head for what we may call the coarse adjustment, and upon movement of the eyes for the fine adjustment—for fixing the neighboring parts of the object.

When we turn the two eyes so as to fix an object on our right we must call into action the external rectus of the right eye together with the internal rectus of the left eye. We can explain the simultaneous contraction of these two muscles only upon the assumption that there exists in the brain a connection between the visual centers and a certain center or nucleus, which in turn is connected with the external rectus of one eye and with the internal rectus of the other eye.

The connection between the visual centers and the muscles must, in fact, be far more complicated than this simple illustration would show. In the various movements of the eyes each muscle must receive its appropriate innervation, for although one or two of the muscles of each eye may play the more important part, such delicate adjustments as are required can only be accomplished through the co-operation of all the muscles.

So intimate is the association of the two eyes that we cannot turn one eye in any direction without a corresponding movement of the other eye.

Listing's Law.—Torsion of the meridians would occur in rotation of the eye by a single muscle, other than the internal or external rectus. As the physiological movements of the eye are not produced by contraction of a single muscle, but by a number of muscles acting in unison, such torsion is of interest chiefly in the study of ocular paralyses. We study the physiological

action of the various muscles, and we thereby learn what effect would be produced upon the rotation by the absence (from paralysis) of any component element.

But torsion also occurs in the physiological oblique movements of the eye. This fact was first shown by *Donders,* who made the discovery by studying the after-images of the eye.

The study of after-images was introduced by *Ruete.* If, in a darkened room, we fasten a narrow strip of red ribbon horizontally on a gray background and gaze for about a minute at this ribbon, upon turning the eye to another part of the gray background, we shall see a greenish complementary after-image of the ribbon. For the study of torsion we place the ribbon on a level with the eyes. After looking at it for a sufficient time we turn the eye into an oblique position, as outward and upward. The after-image of the ribbon will not now be horizontal; it will be obliquely inclined to the horizontal plane. This shows that the meridian of the retina which receives the image of a horizontal line when the eye is in the primary position is not the same meridian which would receive the image of a horizontal line when the eye is in the oblique position; in other words, the retinal meridians have undergone torsion with reference to the vertical and horizontal meridians.

The law of torsions in its fullest sense was first given by *Listing.* When the eye turns from the primary to any secondary position it may arrive at this secondary position either by moving directly to its new position, along the shortest route, or it may make two or more movements before arriving at the final position. *Listing's Law* simply states that no matter how the eye reaches the secondary position under consideration, the torsion is the same as if the eye had turned directly from the primary to the secondary position.*

Therefore in any secondary position which the eyes may occupy we may suppose that they have turned directly to this position from the primary position. It is apparent that in making a rotation in this manner the eye turns about an axis which lies in a vertical plane passing through the centers of rotation of the two eyes. This vertical transverse plane is called *Listing's Plane.* We do not say that all physiological ocular rotations take place around axes in this plane; for this is plainly not so when the eye turns from one oblique position to another. But since the position of the eye in the last secondary position is the same as if it had turned directly from the primary position into this secondary position, we say that *as far as the result is concerned all physio-*

* By secondary position we mean any position that is not primary.

logical rotations may be regarded as taking place around axes lying in Listing's Plane.

This applies to the ocular motions when the eye is directed from one point of fixation to another. When the head is tipped to one side without change of the fixation point the eyes undergo a slight degree of rotation around the visual lines in their endeavor to maintain the meridians in their usual relations. This is shown by *Javal's* experiment with cylindrical lenses. If an eye affected with astigmia is corrected by a lens the axis of the lens will not be in the proper position with regard to the eye when the head is tipped to either side.

Since the change in direction of the meridians which occurs in conformity to *Listing's* law does not result from an actual

FIG. 76

Rubber ball for the study of ocular rotations

FIG. 77

Ophthalmotrope (*Shute*).

For the correct measurement of torsion the observer must look along the visual line as represented by the projecting needle. The outer metal ring represents Listing's plane.

rotation around the antero-posterior axis, it is sometimes called *false torsion*.

The study of torsions is simplified by means of models, called *ophthalmotropes*, which represent the various ocular motions. An inexpensive device for this study is shown in Fig. 76. It consists of a rubber ball painted so as to show the vertical and

horizontal meridians when the eye is in the primary position, and mounted in the frame of a hand magnifying glass.

Convergence

In binocular vision the conjugate movements must always be associated with the proper *convergence* of the visual lines so that these lines shall meet at the point of fixation.

Convergence is effected chiefly by the simultaneous contraction of both internal recti, but in conjunction with the appropriate contraction or relaxation of the other ocular muscles. For the accomplishment of this united action there must be a connection between the visual areas and a center—*the convergence center*—which in turn must have nerve connections with both internal recti, and also secondarily with the nerves of the other ocular muscles.

The greater degrees of convergence are usually associated with downward rotation of the eyes, as in reading. On this account convergence for a near object is accomplished with much less fatigue when the object is below than when it is above the eyes.

In accordance with *Listing's* law there must be positive torsion of each eye when it looks downward and inward, as in convergence for a near object below the level of the eyes. This fact has given rise to much speculation as to its bearing upon physiological vision; that is, as to how we are able to fuse the two images when the meridians of the eye do not occupy the same relative position that they do in distant vision. *Stevens* has presented mathematical evidence that the torsion assists fusion when the object of vision is in the usual position of a book held for reading. *Savage,* on the other hand, who would discard *Listing's* law, believes that there is no torsion, but that this is overcome by the rotary action of the oblique muscles. The question is too difficult and too abstruse to engage our further attention, especially as we must eventually acknowledge that we know almost nothing of the mental process of binocular vision.

Measurement of Convergence.—The degree of convergence is measured by the angle through which each eye must turn from parallelism of the visual lines so that these lines may

pass through the point of fixation. This angle may be measured in degrees, but we shall usually find it more convenient to express it in terms of the meter-angle.

A meter-angle (*ma*) is that angle through which each eye must turn from parallelism of the visual lines so that these lines may meet in the median plane and at a distance of one meter from the interocular base line. If the distance at which the visual lines meet is two meters the convergence is expressed by one-half of a meter-angle; while if the distance is one-half of a meter the convergence is two meter-angles, and so on.

This system has the advantage that in emmetropia the convergence, as expressed in meter-angles, is equal to the accommodation as expressed in diopters.

The chief objection to this unit is that it has no fixed value, since the value varies with the interocular distance. This distance ranges from 50 *mm* to 75 *mm*, and by calculation we find that within these limits the meter-angle varies between $1.4°$ and $2.1°$.

The average interocular distance in the adult is given as 64 *mm*, which gives $1.83°$ as the average value of the meter-angle. This corresponds approximately to the deviation produced by a prism of $3\frac{1}{2}\,\Delta$. Therefore if we use this average as a standard, one meter-angle of convergence is equivalent to the effect of a prism of $3\frac{1}{2}\,\Delta$, *base out,* before each eye, or to the effect of a prism of $7\,\Delta$ before one eye.

Near Point of Convergence.—By the near point of convergence we mean the nearest point for which the eyes can converge. *Landolt* estimates that, as an average, this point lies $\frac{1}{9.5}$ of a meter (*10.5 cm or about 4 inches*) from the interocular base line. *This represents a converging power of* 9.5 *ma.*

Relaxation of Convergence.—Although the simple relaxation of the internal recti will diminish the convergence, the full relaxation can only be accomplished by the simultaneous contraction of the external recti. This implies that there must be a *nerve center for divergence* as well as for convergence, and that these two centers must be in intimate association.

Far Point of Convergence.—In the human race, possessed of binocular vision, absolute divergence of the visual lines does not exist as a normal condition. In distant vision there is no convergence—the convergence point is at an infinite distance.

We might suppose, therefore, that parallelism of the visual lines would represent the maximum relaxation of convergence; but it is not so, for by the interposition of a prism we can show that normal eyes are capable of an actual divergence.

Divergence of the visual axes is expressed as *negative convergence.* The negative range of convergence is normally about one meter-angle. This corresponds to a prism of 3½ △ placed before each eye, with its base towards the nose.

Association of Accommodation and Convergence.—In normal vision every change in convergence is accompanied by a corresponding change in accommodative impulse. In emmetropia vision at one meter is accomplished with 1 D of accommodation and 1 *ma* of convergence; at one-third of a meter there must be exercised 3 D of accommodation and 3 *ma* of convergence, and so on. So intimate is the association between these two functions that exercise of one of them is involuntarily accompanied by a corresponding action of the other.

Although normally associated, accommodation and convergence are not indissolubly connected. With exercise of a fixed degree of convergence the amount of accommodation may, within certain limits, be varied, and *vice versa.*

If a weak concave lens is placed before each eye of an emmetrope, he can still see a distant object clearly by exercise of accommodation while the visual axes remain parallel; but when the strength of the concave lenses is increased beyond a certain limit, either the object will appear indistinct from insufficient accommodation or diplopia will result from convergence of the visual lines. The limit of accommodation with parallelism of the visual lines is slightly more than 3 D (*Donders*) for an emmetrope fifteen years of age.

The addition of a convex lens to each eye in emmetropia would render a distant object indistinct, since no further relaxation of accommodation is possible; but if a near object is viewed, the accommodation may, within certain limits, be increased by concave lenses and diminished by convex lenses, while the convergence remains unchanged. In vision at 33 *cm,* the requisite convergence being 3 *ma,* accommodation may be varied from .5 D (by convex lenses) to 6.5 D (by concave lenses) in an emmetrope fifteen years of age (*Donders*).

The difference between the least and the greatest amount of

accommodation that is possible with a fixed convergence constitutes the *relative range of accommodation.*

Donders determined the relative range of accommodation in various individuals with different refractive conditions, and

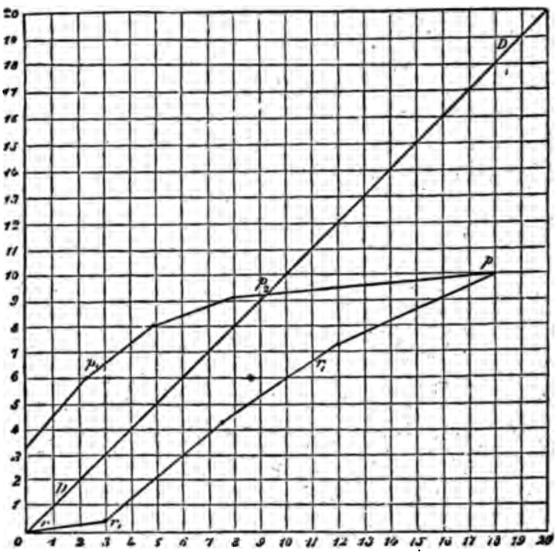

FIG. 78
Accommodation and convergence (*Donders*).

expressed his results in what is called the graphic method. This method is illustrated in Fig. 78, which is *Donders's diagram* of the relative range of accommodation in an emmetrope of fifteen years of age.

In the chart the diagonal line represents the convergence; p_1 p_2 p represents the maximum of accommodation possible with a given convergence; and r r_1 r_1 represents the minimum of accommodation. The accommodation in diopters is read from the vertical column of figures, and the convergence in meter-angles is read from the horizontal markings.

Hess has more recently made studies of the relative accommodation, and by more exact means than were used by *Donders* has obtained a somewhat different result. His chart is shown in Fig. 79. We see that the accommodation lines are parallel to the convergence line.

As the accommodation can be varied while convergence is unaltered, so the convergence may, within certain limits, be increased or diminished without change of accommodation. This has already been shown in connection with the diverging power of the eyes. By means of prisms (*bases in*) a divergence of 1 *ma* may be made when the accommodation is completely relaxed. By means of prisms also (*bases out*) a convergence of about 2 *ma* may be made without exercise of accommodation. With 3 D of accommodation convergence may vary from zero (parallelism) to about 6 *ma*. The difference between the least and greatest convergence with a fixed amount of accommodation represents the *relative range of convergence.*

The diagram which gives the relative range of accommodation may also be used to show the *relative range of con-*

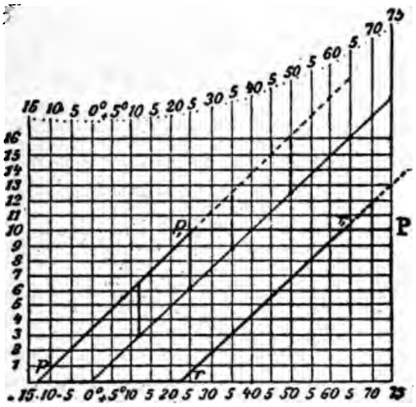

FIG. 79
Accommodation and convergence (*Hess*).

vergence; for the horizontal scale records the greatest and least convergence which is possible with a fixed amount of accommodation.

This latitude in the relative accommodation and convergence is of great importance, for it is through this variation that comfortable binocular vision is frequently possible in ametropia, and that the accustomed relation in ametropia may be disturbed by correcting lenses with at least only temporary discomfort.

Accommodation and Convergence in Side Vision.— The relation between accommodation and convergence undergoes a change when we move our eyes from an object in the median plane to either side of this plane. Further, the question arises as to the manner of accommodation in such vision; that is, whether a greater amount of accommodation is used with one eye than with the other, or whether vision is blurred in both eyes, or whether one eye accommodates properly for the object while the other, exercising the same degree of accommodation, receives a blurred image. It is generally thought that the last is Nature's method, and that the eye which is farther from the object, requiring the less accommodation, adapts itself for the object. We do not, however, ordinarily look intently at objects much removed from the median plane, for when an object so situated attracts our attention, we turn our head towards the object.

CORRESPONDING POINTS

The Horopter

We have learned that in binocular vision the image of the point of fixation falls upon the center of the fovea of each eye. If from any cause the image of fixation falls upon the fovea of one eye and upon some other part of the retina of the other eye, *double vision* results. The centers of the two foveas are *corresponding points* of the two retinas, but any other part of the retina of one eye is a *disparite point* with reference to the fovea of the other eye. Owing to the nerve relationship between the retinas and the visual centers, we cannot form a single impression from the two images as formed upon disparite points of the retinas.

A great amount of labor was expended by *Helmholtz* and others in the study of the *horopter*. By this term we mean the surface containing all the points which would be seen singly for any fixed adjustment of the eyes; that is, the horopter contains all the points whose images would fall upon corresponding points of the two retinas.

In any given adjustment of the eyes there would always be a large part of the field of vision in which objects would not fall upon corresponding points; but as we do not ordinarily see such outlying objects double, it is of no importance that they do not

lie in the horopter. Furthermore, we are not warranted in assuming that corresponding geometrical points are so correlated with the visual centers that these same points correspond in a physiological sense. In fact, if we should thus determine the corresponding points with the eyes in the primary position, the same points would not correspond with the eyes in convergence.

Why then do we not see doubled the objects which do not lie in the horopter? The answer is that vision is a process of the mind. The human race has acquired the faculty of binocular vision. We have learned to fuse the two images of direct vision, but we devote only slight attention to the objects of indirect vision, and if a double impression is made on the visual areas, it is not conveyed to the centers of consciousness. By properly directing our attention we can experimentally elicit double vision under certain circumstances when we should not ordinarily be aware that it existed.

NORMAL MUSCULAR EQUILIBRIUM

In a state of complete repose the directions of the visual lines are determined by the relative lengths of the extra-ocular muscles when these are all in complete relaxation. Entire absence of innervation of these muscles exists, however, only during closure of the lids, in sleep (natural or narcotic) and in blindness. Examinations show that under these conditions the eyes usually assume more or less divergence in accordance with the divergence of the orbits, which would give in man, as in the lower animals, a natural divergence of the eyes, if this tendency were not overcome by the capacity for binocular single vision.

But since complete muscular relaxation does not occur in physiological vision, the effect of such relaxation upon the directions of the visual lines is of minor importance. The question is, *What is the position of equilibrium of the ocular muscles during vision?* In distant emmetropic vision no accommodation is required and the visual lines are parallel; convergence must be exactly neutralized by the external recti, and the vertical adjustment must exactly correspond in the two eyes. If the relation between accommodation and the extra-ocular muscles is perfectly adjusted, the eyes will assume the proper position for binocular single vision, even though one eye may be excluded

from vision. This is the ideal (normal) muscular equilibrium; it is called *orthophoria.*

On the other hand, binocular single vision may be habitually performed, either with or without discomfort, and yet when one eye is excluded from vision it will involuntarily move inward (*esophoria*) or outward (*exophoria*), or upward or downward (*right* or *left hyperphoria*). Any such deviation from orthophoria is called *heterophoria.*

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PART III

ERRORS OF REFRACTION

CHAPTER X

OPTOMETRY OF THE REFRACTIVE APPARATUS

The various methods which are at our command for determining the refractive condition of the eye may be divided into two general classes: (1) subjective methods, and (2) objective methods. In the former method the examiner is guided by the statements of the person undergoing examination, while in the latter he relies solely upon his own judgment.

Subjective Methods

Optometers Based upon the Action of a Convex Lens.—A single convex spherical lens placed before the eye constitutes the simplest of optometers.

We know that if the distance from the lens to an object is greater than the focal length of the lens, rays from the object will enter the eye in convergent pencils, and, consequently, will be focused on the retina only when the eye is *hyperopic.* If the distance from the lens to the object is equal to the focal length of the lens, the rays from any point of the object will be parallel when they enter the eye, and will be focused on the retina of an *emmetropic* eye. Finally, if the distance between the object and the lens is less than the focal length of the lens, rays from any point of the object will enter the eye in divergent pencils, and can be focused on the retina only when the eye is *myopic* or exercising accommodation. If, therefore, the object is so small that it cannot be distinguished unless its image is accurately formed on the retina, we can judge by the position of the lens whether an eye is hyperopic, emmetropic, or myopic.

Optometers of this kind have two disadvantages: (1) The

magnifying power is variable; and (2) the nearness of the test object provokes an accommodative impulse, by which the result of the examination is rendered uncertain.

Optometers Based upon the Principle of the Opera Glass or Galileo's Telescope.—Optometers of this kind consist of a combination of a strong concave lens, or *eye-piece,* with a weaker convex lens, or *objective.* By varying the distance between the two lenses different refractive effects are produced. If the two lenses are in contact, the effect of the concave lens, which is the stronger, predominates, and the combination is equivalent to a concave lens whose strength is equal to the difference in power between the two lenses; but as the convex lens is withdrawn from the eye its refractive effect in distant vision increases, and in a certain position the two lenses exactly neutralize each other. By further withdrawal of the convex lens the combination finally becomes equal to a convex lens.

According as a distant object appears distinct to the eye under examination when the foregoing combination has a *convex, a plane, or a concave effect,* the eye is *hyperopic, emmetropic* or *myopic,* and from a suitably constructed scale the degree of ametropia can be determined. But this test also lacks accuracy because the magnifying power of the convex lens increases as it is withdrawn from the eye.

Optometers Based upon Scheiner's Experiment.—When one looks through minute openings at a small object placed at a distance for which the eye is not adapted, the object

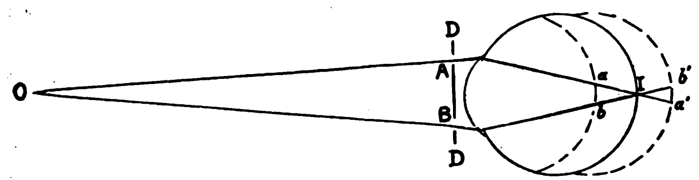

FIG. 80
Scheiner's Experiment

appears multiplied, for each opening furnishes a separate image. This phenomenon, called *Scheiner's experiment,* is illustrated in Fig. 80. Let O represent a point of light, D D the diaphragm, and A and B two openings in the diaphragm. If I is conjugate to O, and if the retina intersects the axis at I, there will

be a single image of the point O. If the retina lies in front of I, the light passing through the opening A will fall upon the retina at a and that passing through B will fall upon b, and since an image on the retina above the axis corresponds to an external object below, and *vice versa,* it is apparent that the image which is formed by the light passing through the upper diaphragm appears below while the image formed by the light passing through the lower diaphragm appears to be above the axis. In other words the two images are *inverted* with respect to the openings in the diaphragm.

If, on the other hand, the retina lies behind I, the image a' will be below and b' will be above, and in projecting these images externally through the nodal point of the eye the relative position of the two lights will be the *same* as the openings in the diaphragm.

We may therefore use this phenomenon to determine the refractive condition of the eye. We place a red glass before one of the openings so as to distinguish the two images. The point of light is furnished by a small flame or electric light six meters distant from the eye. When a single image is seen the eye is *emmetropic.* When two images are seen, the relative position being opposite to that of the openings in the diaphragm, the eye is *hyperopic.* When the relative position is the same as that of the two openings the eye is *myopic.* By placing the proper lens before the eye the two images may be united and the degree of ametropia measured thereby.

The optometer of Thomas Young, which *Tscherning* has found valuable in the study of accommodation, is based upon the principle of Scheiner. The method of producing the multiple images with this optometer is shown in Fig. 81. If we hold the diaphragm before the eye so that two or more of the slits come within the pupillary area while we look at a straight line, whose length lies in the line of vision, we see a separate line for each slit, and these lines converge to the point which is conjugate to the retina. (Fig. 81.)* While this optometer is of great scientific interest it is not suitable for the practical determination of the refractive condition.

Optometers Based upon Chromatic Aberration.— In the application of this property the examinee looks at a small

*On account of the spherical aberration of the eye the lines do not actually meet in a common point.

round area of light five or six meters distant. The eye is covered with cobalt blue (purple) glass, which allows both blue and red light to pass through it. The blue rays, being more strongly refracted than the red rays, are brought to a focus sooner than the red. If the blue rays are focused slightly in front of the retina and the red rays slightly behind it, the image of a point of light

a

b

FIG. 81

(*a*).—Diaphragm of Young's optometer.
(*b*).—Appearance of a line as seen with Young's optometer.

will be a small diffusion circle, in which both red and blue light will be present, and the point will be seen as a small purple spot. This is the condition in *emmetropia.* If the eye is *hyperopic,* the blue rays will be more nearly focused than the red rays. Hence, there will be formed on the retina a diffusion circle, the central part of which will contain both blue and red rays, but more blue than red, and the outer part will contain only red rays. The image will, therefore, appear as a *central blue area* surrounded by a *red band.* On the other hand, in *myopia,* both red and blue rays having passed their foci before reaching the retina, the blue will be more diffused than the red light. Hence, the central part of the diffusion circle will contain mostly red and the outer part only blue light. The image will, therefore, appear as a *central area of red* surrounded by a band of *blue* light.

The degree of ametropia may be ascertained by placing before the eye such a lens as will render the image uniformly purple throughout. This lens is the measure of the ametropia.

Optometers Based upon the Measurement of the Retinal Diffusion Circles.—Two distant points of light

separated by a sufficient interval will appear separate and distinct to the emmetrope; but to the ametrope the points will appear as two bright disks whose size will increase with the degree of ametropia. If the diffusion circles are sufficiently large, these disks will appear to overlap, and the distance between the two lights must be increased in order that the images may be entirely separated. From a suitably constructed scale the degree of ametropia may be estimated by observing the least distance which may intervene between the two lights while they are seen as separate. *Thomson's ametrometer* is based upon this principle.

Optometry Based upon Movement of the Diffusion Image on the Retina.—If one looks at a distant point of light through a stenopæic slit which is moved from side to side, he sees an apparent movement of the light except when his eye is so adapted as to focus the light on his retina. This is apparent from Fig. 80, which was used in illustration of Scheiner's experiment. We may assume that A represents the first position of the stenopæic opening and B the position into which it is subsequently moved. If the eye is *hyperopic,* the retinal image of O will fall at a in the first position, and as the slit is moved to B the image will move to b. If the eye is adapted for the point O, the image remains at I in all positions of the slit. If the eye is *myopic,* the image moves from a' to b' when the slit moves from A to B. Hence, if O is a distant point of light the eye is *hyperopic* or *myopic* according as movement of the slit causes an *opposite* or a *like* displacement of the light. The lens which neutralizes the displacement measures the ametropia. This test, under the name of *kinescopy,* has been advocated by *Holth.*

Optometry Based upon Visual Acuteness.—The foregoing methods of optometry are of scientific interest, and some of them are occasionally used in practical work, but for general use the one subjective method which is indispensable consists in testing the visual acuteness with trial lenses.

Visual acuteness is measured by the least interval which may exist between two points while they are still distinguished as separate. It is apparent that this interval, as measured on the retina, cannot be less than the diameter of one sentient element of this organ; for when two adjacent elements are illuminated no interval of darkness can exist between the two points.

The interval between retinal cones in the macular region is

probably about 0.002 *mm,* and this length subtends, at the nodal point of the eye an angle somewhat less than one-half of a minute. Since an object subtends at the nodal point the same angle which the image subtends at this point, we should suppose that the *minimum visual angle* for distinguishing points would be about one-half of a minute; but, because of the imperfections of the eye, we find that, even under favorable circumstances, it is rarely possible for us to distinguish points separated by so small an interval.

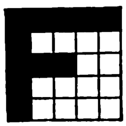

FIG. 82

Test letter constructed according to Snellen's principle.

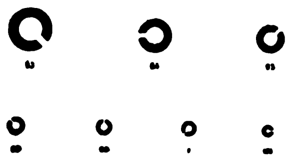

FIG. 84

Landolt's Chart

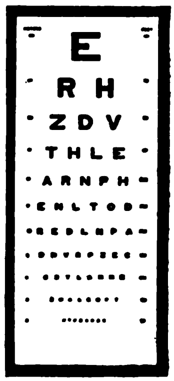

FIG. 83

Test Card

The astronomer *Hooke,* in 1674, made the first investigations to ascertain the minimum visual angle. Taking the multiple stars as the points, he found that in no case could any interval be distinguished when the angle was less than one-half of a minute, and in most cases an angle of one minute was required in order that the interval could be distinguished.

For practical purposes a series of parallel lines, also used by Hooke, affords a more convenient means of testing visual acuteness. The least angle which, under favorable circumstances, may separate black lines on a white ground while the interval between them is perceived is about fifty seconds (50″). This angle corresponds to a linear distance on the retina of slightly more than 0.004 *mm;* that is, it is more than twice the diameter of one retinal cone.

In accordance with these facts, *Snellen,* in 1862, constructed a series of test-letters, which he called *optotypes,* for the examination of visual acuteness. The whole letter in each case subtends

an angle of five minutes when in the proper position, and each stroke of the letter subtends an angle of one minute (Fig. 82).

Since many eyes do not have the normal visual acuteness, we have letters of different sizes, the distance at which the letters subtend an angle of five minutes being denoted for the letters of each separate size (Fig. 83).

In order to facilitate relaxation of the accommodation we place the letters at a distance of five or, preferably, six meters from the eye undergoing examination.

If the distance is six meters and if the examinee can read those letters which subtend a visual angle of five minutes, the eye possesses *normal visual acuity*. This is recorded thus: $V = 6/6$ or $V = 1$. But if at this distance the examinee can read no smaller letters than those which should be read at nine meters, the visual acuteness is recorded by the expression $V = 6/9$.* The *distance at which the examination is conducted is the numerator,* and the distance at which the smallest distinguishable letters *should be read* is the *denominator* of the fraction expressing the visual acuteness.

We have seen that the minimum visual angle is somewhat smaller than the angle required for normal ($V = 6/6$) vision as indicated by Snellen's test-letters; moreover, it is not necessary for one to see distinctly all the lines of a letter with which he is familiar in order to read the letters correctly. It not infrequently happens, therefore, that one can read at a distance of six meters the letters which subtend the five-minute angle at four meters, or even at three meters, and we may thus have $V = 6/4$ or $V = 6/3$. It is, in fact, the rule in young persons for the visual acuteness to exceed the normal as indicated by the test-letters. After middle age the visual power undergoes a diminution and vision exceeding 6/6 does not so often occur.

Because visual acuteness so frequently surpasses the standard fixed by Snellen, his plan has been modified by the substitution of a four-minute angle. Nothing is gained by this substitution of a standard, which, while more accurate for the young, is too high for middle and old age. The *average normal visual acuteness* is sufficiently approximated by Snellen's five-minute-angle stand-

*The method sometimes adopted of expressing the visual acuteness as a decimal fraction has the disadvantage of not indicating the distance at which the test has been made.

ard, and any alteration, unless universally adopted, can only lead to confusion.

Of the other modifications of Snellen's system, it suffices to mention that of *Landolt,* who has substituted for the alphabetical characters a circle having an opening in its circumference (Fig. 84). The size of the hiatus conforms to the minimum visual angle of Snellen. The character is varied by placing the hiatus in different positions. This plan has a number of advantages from a scientific point of view over the use of letters; yet, because of the convenience of the latter, it is probable that they will continue in common use. *Landolt's* charts are, however, especially convenient for illiterates.

Since some persons very soon memorize the test-letters, it is well to have a number of test-cards, and in the selection of these it is important that we have all the cards uniform in respect to the size and distinctness of the letters which are to be read at the specified distance.

In making use of this method of examination care must be taken to provide suitable illumination. If sufficient daylight is not available, gas or electric light may be used, proper shades being employed in order that the direct rays from the lamp will not reach the eyes.

Each eye should be tested separately and the eye not undergoing examination should be excluded by an opaque disk.

When it is desired merely to test the visual power without the aid of lenses, all that is necessary is to place the individual and test-card in proper position and to observe the smallest letters which he can read. The distance at which the letters are read divided by the distance at which they ought to be read expresses the visual power.

But when our object is to discover the refractive condition of the eye, we must select and place before the eye that lens which produces the highest obtainable degree of vision. Furthermore, since we wish to compare the visual acuity with that of a normal emmetropic eye, we must endeavor so to place the lens that the retinal images will be of the same size as that of the emmetropic eye.

The lens which, when placed in proper position (15 *mm from the eye*), *affords the maximum visual power measures the*

ametropia, for it is evident that the highest power of vision will be obtained when the image is accurately focused on the retina.

Trial Lenses.—In order to facilitate the selection of the proper lens, the examiner must provide himself with a case of trial lenses. This consists of pairs of convex and concave spherical and cylindrical lenses, prisms, plane and colored glasses, opaque disks, stenopæic disks, trial frames for holding the lenses before the eye, and other accessories.

In the complete case the interval between lenses is 0.125 D for those below 2 D in strength; 0.25 D for those between 2 D and 5 D; 0.50 D for those between 5 D and 8 D; and 1 D for those between 8 D and 23 D, the last named being the highest power usually furnished in the case, and this only in the spherical lenses. The cylindrical lenses ordinarily do not exceed 6 D or 8 D in strength, though more elaborate cases are made in which these lenses are supplied up to 16 D.

The dioptric power is marked on each lens, the plus (+) sign being used to denote convex, and the minus (—) sign to denote concave lenses. In the cylindrical lenses the position of the axis is marked on the glass, and, in order that this position may be determined at a glance, the peripheral part of the lens is usually rough-ground in a direction parallel to the axis.

Determination of the Power and Center of a Lens.—It is obviously necessary that we should be able to determine quickly the kind and power of any ophthalmic lens, and the position of its optical center.

The most common method of ascertaining the power is by *neutralization* with the trial lens of equal denomination, but of opposite sign.

If we hold a convex lens in front of the eye and through it look at a distant object, an image of the object, more or less blurred will be seen. If the optical center of the lens lies in the line of vision, no lateral displacement will result; but if the lens is moved laterally it acts like a prism with its base towards the center of the lens, and the greater the lateral movement, the greater will be the prismatic effect. Since a prism causes an apparent displacement towards its apex, it follows that as the lens is moved to the right the object appears to move to the left, and *vice versa.*

On the other hand, if a concave lens is substituted for the

convex lens, the object will appear to move in the same direction as the movement of the lens.

By selecting from the trial case that lens which annuls the lateral deviation, we have the effect of plane-glass. The lens whose power is sought is of the *same* denomination but of *opposite* sign to that which produces this effect.

To determine the position of the center of the lens, we view a straight line (as the edge of a test-card) through the lens, and observe the position of the lens in which there is no break in the straight line as seen through the lens and beyond its borders. Marking the points where this line appears to cut the lens, we connect these points by a straight line drawn in ink. This line passes through the center of the lens. Repeating this process in another meridian, we have two lines passing through the center, and their point of intersection must indicate the position of this center.

In a cylindrical lens the lateral deviation takes place at right angles to the axis of the lens, and any line making an oblique angle with this axis undergoes an angular deviation, the explanation of which has already been given (p. 84). Hence, the *direction* of the axis is determined by observing that direction in which a lateral movement of the lens produces no apparent displacement of an object. The *position* of the axis is determined by observing the points at which the unbroken line (as seen through the lens and beyond its edges) cuts the lens; the straight line joining these points represents the axis of the lens.

We may also determine the power of a lens by direct measurement of the curvature of its surfaces with the aid of a *lens-measure* or *spherometer.*

While either of these two methods may be used with satisfaction in ophthalmological practice, each of them may lead to false deduction unless its limitations are appreciated. In the application of neutralization error may occur from neglect of the distance between the optical centers of the two lenses. In the stronger lenses this error is considerable, and for such neutralization is not reliable, except in plano-curved lenses, in which the two curved surfaces may be placed in apposition. In the use of the spherometer error is liable to occur from the variation which exists in the index of spectacle-glass used by different manufacturers; furthermore, the spherometers which are commonly sold are so

inaccurately adjusted that they cannot be relied upon to denote fine distinctions of lens power.

Cycloplegics.—Being provided with test-letters and trial lenses, we have still another matter for consideration when we undertake to make use of this method of examination. It is our aim to determine the refraction of the eye with the ciliary muscle in a state of complete relaxation. On this account the letters should be placed not less than five meters from the examinee; but in young subjects even this precaution does not ensure relaxation, and other means must often be employed.

Certain drugs possess the property of temporarily paralyzing the action of the ciliary muscle. Since they also dilate the pupil, they were formerly called *mydriatics;* but the discovery of substances such as *cocain* and *euphthalmin,* which dilate the pupil but only partially affect the ciliary muscle, has rendered necessary a means of distinction between drugs which dilate the pupil and those which also paralyze the ciliary muscle. The latter are called *cycloplegics.*

The principal cycloplegics are *atropin, daturin, hyoscyamin, duboisin, scopalamin* and *homatropin.* Of these the effect is most persistent in the case of atropin (fifteen days) and most transient in the case of homatropin (from one to two days). Next to homatropin comes scopalamin, whose effect lasts six days, being much diminished in intensity by the second day. Of this list of drugs two, *atropin* and *homatropin,* are sufficient for routine use in the determination of refraction.

The effect of belladonna, from which the alkaloid atropin is derived, upon the pupil and the accommodation has long been known. A thorough study of the action of atropin on the accommodation was made by *Donders.* He found that a single drop of a solution containing one part of atropin sulphate to one hundred and twenty parts of water was sufficient to produce complete mydriasis and complete cycloplegia in a healthy eye. The mydriasis, which occurred first, reached its maximum in about twenty-five minutes, and remained stationary for thirty-six hours, after which it slowly diminished, the pupil regaining its normal size in about fourteen days. The cycloplegic effect was scarcely noticeable until the time of maximum mydriasis, when accommodation rapidly failed, being totally paralyzed at the end of one and a half hours. Total paralysis lasted about forty hours; after this

accommodative power gradually returned, regaining its full amplitude after the expiration of about twelve days.

The weakest solution of which a drop will cause paralysis of accommodation is, according to Jaarsma, 1:1200. The duration of this action is twenty-four hours, while the effect on the pupil lasts for ninety-six hours. The same author states that one drop of a solution in the proportion 1:80,000 will produce *mydriasis,* the effect lasting twenty-four hours (*Landolt*).

Although so small a quantity of the drug suffices to produce its maximum effect in a normal eye, several instillations should be made before the refraction is tested. In this way the tendency to spasmodic contraction of the ciliary muscle, which is so frequently present in young persons, may be overcome. A one-half per cent solution may be prescribed, and one drop of this should be instilled three or four times a day for two days or longer. By this means constitutional effects of the drug may be avoided and relaxation assured.

There sometimes results from the use of atropin the condition known as *atropinism*—an irritation and inflammation of the conjunctiva. It usually occurs only after the prolonged use of the drug in inflammatory states; seldom from the brief use for testing refraction. The cause of this condition is a matter of doubt. It is thought that strongly acid or alkaline reaction of the solution and the presence of micro-organisms are at least contributory elements. Therefore, the solution should be freshly prepared and, as far as possible, sterile.

Because of the great persistence of the effect of atropin, it is a most inconvenient drug for use in refractive work. It should, therefore, be reserved for those cases in which there is reason to believe that homatropin will be ineffective; that is, for young children and for those adults in whom complete relaxation has not followed the use of the latter drug; or, again, for those persons in whom it is desired to produce a prolonged, enforced rest of the accommodation.

Homatropin is a derivative of atropin, being obtained from the latter through a complicated chemical process. The alkaloid is an oleaginous liquid, which in combination with hydrobromic acid forms a crystallizable salt, and it is this salt that is commonly used in ophthalmological practice.

Complete relaxation of the accommodation may be obtained

with homatropin-hydrobromate, except in certain cases of obstinate spasm, such as occasionally occurs in childhood, and in inflammatory conditions. In those cases in which homatropin is applicable for measuring the refraction, relaxation may be assured by instilling into the conjunctival sac one or two drops of a 1.5 per cent solution every ten minutes until six applications have been made. In one hour after the last application the accommodation will usually be entirely paralyzed. The maximum effect on the accommodation lasts not more than a few hours, and at the expiration of thirty-six hours near work may usually be resumed.

A convenient method of application consists in the use of gelatin disks, as recommended by *Casey Wood.* A variety of drugs may be thus incorporated. A suitable combination for the determination of refraction consists of 1/50 grain of homatropin (alkaloid) and 1/50 grain of cocain-hydrochlorate. One disk of this composition is sufficient to insure relaxation except in unusual conditions. In children a second disk should be inserted one hour after the first application. The cocain, though useless alone as a cycloplegic, increases the effect of the homatropin.

Method of Conducting the Test with Trial Lenses.—In making use of the test by trial lenses a preliminary examination is usually conducted without cycloplegia.

The examinee being properly seated, and the other conditions, as described, being fulfilled, he is asked to read the test-letters, beginning with the largest and proceeding to successively smaller letters until he reaches those which he cannot clearly distinguish. If at a distance of six meters he can read all the letters which, as indicated on the card, are intended to be read at this distance, his vision is normal. Normal vision is possible only if the image of the letters falls accurately upon the retina.* The eye must, therefore, be adapted for this distance; that is, there is 1/6 D of myopia. But the difference in position of the retina in this amount of myopia and in emmetropia is inappreciable, and we regard the eye as adapted for an infinite distance. The refractive condition, therefore, must be either that of ***emmetropia*** or of ***hyperopia with exercise of accommodation.***

To determine which of these two conditions is present, we place before the eye a convex spherical lens of .50 D. If vision

*Strictly speaking, a slight degree of ametropia cannot be excluded until it is proved that a weak lens does not afford still better vision, for, as we have learned, in many cases the acuteness reaches 6/4 or even 6/3.

is not rendered worse by this lens, it is clear that accommodative action has been replaced by the convergent power of the lens. To ascertain whether accommodation is still being exercised, we add stronger and stronger lenses until we obtain the strongest lens which does not render vision worse.

Under favorable circumstances the accommodation may be totally relaxed, being replaced by the convex lens, and the dioptric power of this lens is the measure of the hyperopia; but frequently in young persons a spasmodic condition of the ciliary muscle arises.* If this condition cannot be otherwise excluded, a cycloplegic must be employed.

If, in relaxation of the ciliary muscle, distant vision is normal without a lens, and is not made to exceed the normal standard by the addition of a lens, the eye is *emmetropic.*

If the vision, having been found normal at the preliminary examination, is below normal in cycloplegia, there is either hyperopia or astigmia or both. If vision is made normal with the aid of a convex spherical lens, this lens measures the hyperopia; but if the spherical lens does not improve vision, or if, while it improves vision, it does not render it normal, astigmia is present. If this is regular it may be corrected by means of a cylindrical lens.

If vision is below normal without cycloplegia we must differentiate between five possible conditions.

(1) The eye may be hyperopic and without sufficient accommodative power to focus parallel rays upon the retina. If this is so, vision will be rendered normal, or at least improved, by means of a suitable convex spherical lens.

(2) The eye may be emmetropic or hyperopic with an excess of accommodative action; that is, the condition simulates myopia, and vision will be rendered worse by a convex lens and improved by a concave lens.

(3) There may be true myopia.

(4) There may be astigmia, either alone or in combination with any of the aforementioned defects.

(5) The defective vision may be due to no error of refraction, but to lack of transparency of the media or to anomaly of the retina, optic nerve, or brain.

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* There is less tendency to spasmodic action of the ciliary muscle when both eyes are used than when one eye is excluded. It is sometimes advisable, therefore, to make the final test on the two eyes simultaneously.

Although we have these five conditions presenting the common symptom of defective distant vision, it is not difficult to make the decision as to which of these conditions exists.

In the first case, the fact that a convex spherical lens improves vision reveals hyperopia.

In the second case, the condition will be suspected in a young subject and the accommodation paralyzed, when the true condition of *hyperopia* or *emmetropia* will appear.

In true myopia, as in the previous case, vision is improved by a concave spherical lens. Having excluded, either by cycloplegia or by the age of the individual, spasmodic action of the accommodation, we place before the eye successively stronger concave lenses until we obtain that lens which affords normal or maximum vision. This lens measures the degree of myopia. But as we found it necessary in estimating hyperopia without cycloplegia to select the strongest convex lens, so, under the same condition, we must exercise care to select the *weakest* concave lens which affords maximum vision, for otherwise the myopia will be overestimated, accommodation being exercised to overcome the excessively strong concave lens.

The next and last of the refractive errors to which defective distant vision may be due, is *astigmia.* We suspect this when neither a convex nor a concave spherical lens affords normal vision. The astigmia may be regular or irregular. The former occurs, as we have learned, when there is asymmetry of one or more of the refracting surfaces. Pathological irregular astigmia is most frequently the result of corneal inflammation, whereby the regularity of surface has been destroyed. Since this kind of astigmia cannot be corrected by a lens, its determination cannot be accomplished by the subjective method with which we are now concerned. Our attention is therefore for the present confined to *regular astigmia.*

The stenopaeic disk is an opaque disk, in which there is cut a slit 1 *mm* in breadth and 10 *mm* in length. This device may be used for determining the principal meridians. When placed before the eye the stenopæic disk permits light to pass into the eye unobstructed in the direction of the length of the slit, while at right angles to this all peripheral rays are excluded. Practically we may regard all the entering rays as lying in the meridian which corresponds to the length of the slit, and by

turning the slit in various directions we can find that meridian in which vision is best. This is the meridian in which the eye is emmetropic, or most nearly so. This method is not very much used, as, owing to the small amount of light which can enter the eye, the normal visual acuity is not attained.

Another device for the detection of the principal meridians of astigmia is *a chart having groups of parallel lines lying in different directions.* We know that a straight line appears distinct to an astigmope only when the line lies at right angles to the

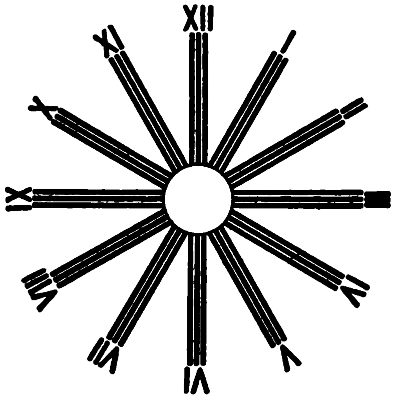

FIG. 85
Clock Dial Chart

meridian in which it is accurately focused, and that the meridian of greatest distinctness is that in which the refraction needs correction. If, therefore, we have groups of equally distinct lines radiating from a center, we can ascertain the principal meridians from the relative distinctness with which the groups of lines are seen.

Charts of this kind were first used by *Javal.* They were subsequently improved and elaborated by *Green,* and the dial shown in Fig. 85 is known as *Green's clock dial chart.* Other charts similar in principle to the clock dial are also used.

In this method of finding the principal meridians we place the chart at a distance of six meters from the examinee, who is directed to state which group of lines appears most distinct. If he can see none of the lines clearly we endeavor to find a spherical lens—trying convex lenses first—which makes one group of lines

distinct. The group at right angles to this will be the most indistinct if astigmia exists, and these two groups mark the principal meridians. *The direction in which the lines are most indistinct is that which is corrected by the spherical lens.*

In hyperopic astigmia many persons can bring first one and then another group of lines into distinctness by varying the accommodation. In order to obviate this, resort may be had to the *fogging system,* which consists in over-correcting the hyperopia and noting the direction in which the lines are least blurred and that in which they are most so. These two directions mark the principal meridians, and by a gradual reduction of the over-correction the true state of refraction is determined.

If the principal meridians cannot be determined with certainty in this way we must resort to paralysis of the accommodation by means of a cycloplegic.

Many ophthalmologists place great reliance upon the clock dial or similar chart; others find it easier to determine the principal meridians by resorting at once to the cylindrical lens, rotating it before the eye until the position is found which gives the greatest improvement of vision. This is the method which I adopt, as I have found the radiating lines unsatisfactory in practical work. Many persons will, from inattention, fail to note a difference, even in marked astigmia, in the various lines, while others will never acknowledge that all are alike after a most careful correction of the refractive error.

Returning now to our example, in which distant vision is defective and is not made normal by any spherical lens, we proceed to ascertain whether astigmia is present. We may begin by using the stenopæic disk or the clock-face chart, or we may proceed to the trial of cylindrical lenses, trying first convex lenses.

If we find that vision is improved by a cylindrical lens we continue the process until we find the lens and the position which afford the best vision. We may then corroborate the result with the clock-face chart—all the lines should be clearly seen and with equal distinctness.

In astigmia complicated with hyperopia or myopia it is not always easy to determine the exact spherical and cylindrical elements which constitute a perfect correction. Having obtained an approximate correction, we proceed to ascertain whether vision is improved by the addition of a weak convex spherical lens (.25

D or .50 D). If this does not cause improvement, we next add a weak convex cylinder, axis parallel to that of the cylinder already before the eye. If this lens does not improve vision, its axis is turned at right angles to that of the other cylinder. This increases the convexity or decreases the concavity of the spherical element, while it reduces the power of the cylinder. If this also fails to cause improvement, a concave cylinder is next selected and placed first with its axis parallel to that of the lens already found, whereby the convexity of the *cylindrical* element is diminished. If this does not cause improvement, the axis is turned through ninety degrees, whereby the convexity of the *spherical* element is diminished, while the power of the cylinder is increased.*

If a change in the cylinder is indicated by any of these additions, the axis of this revised lens must be shifted slightly until the position of maximum vision is obtained. If none of these additions brings vision up to the normal standard, we finally try the experiment of reducing the spherical convexity by adding a weak concave spherical lens. If normal vision cannot be obtained by any combination of spherical and cylindrical lenses, we conclude that there exists some defect which is incapable of correction by lenses. For the diagnosis of the particular condition which may be present other methods of examination must be employed.

Notation of the Axis of a Cylindrical Lens.—The position in which a cylindrical lens is placed is indicated by the angle which its axis makes with a certain fixed line. In America the usual method is in accordance with the notation of angular magnitude as universally employed in mathematical science (Fig. 86), and an American optician would, unless otherwise instructed, use this notation in filling an order for lenses.†

Other systems, which are used in Europe, are illustrated in Figs. 87 and 88.

Objective Methods

Since our aim in ascertaining the refractive condition is to prescribe suitable lenses, it might seem as if the foregoing method, in which the lenses are actually placed before the eye, would

*The cylindrical changes may be made with the crossed cylinder (*Jackson*). This consists of a convex cylinder (.25 D.) combined with an equal concave cylinder, the two axes being at right angles.

† If there is a probability that the glasses will be made by an optician of one of the European countries, the axes should be diagrammatically indicated.

answer all requirements for the selection of glasses; and, in truth, in the final decision as to the proper glass, preference must ordinarily be given to this test. But, owing to the fact that many

FIG. 86

Ordinary Method of Axis Notation

In each eye the position of the axis is denoted by the angle which it makes with the horizontal line, this angle being always measured from the right-hand side of the observer (left-hand side of the patient). The numbering thus runs from 0° to 180°, starting at the nasal side in the right eye and at the temporal side in the left eye. The horizontal axis is always denoted by 180° or 0°, the vertical axis by 90°.

patients lack intelligence, and that some purposely mislead the examiner, and to other difficulties, it is of the utmost importance

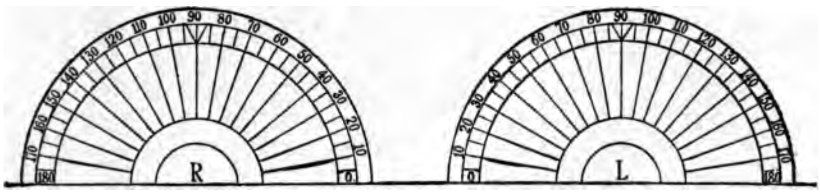

FIG. 87

Symmetrical System of Axis Notation

The zero line is horizontal, and the deviation of the axis from this line is measured from the nasal side for each eye.

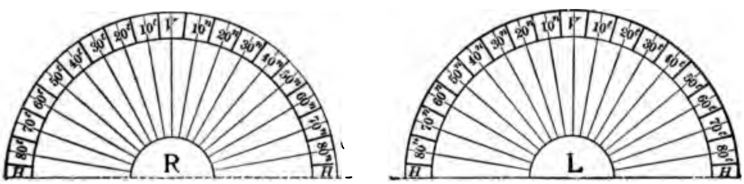

FIG. 88

Tempero-nasal System of Axis Notation

The zero line is vertical, and the deviation of the axis from this line is measured temporalward (*t*) or nasalward (*n*).

that we should be able to determine the refraction independently of the assertions of the patient.

The first of these objective methods is that in which use is made of the *direct method of ophthalmoscopy.*

For conducting this test the examiner must be provided with an ophthalmoscope of at least moderate completeness; that is, the instrument must be equipped with a sufficient number of lenses to enable him to see the fundus clearly, ***without any exercise of accommodation***, whatever may be the refraction of the examining and the examined eyes. The two most popular instruments for general use are *Loring's* (Fig. 89) and *Morton's* (Fig. 90).

In the explanation of the principles of ophthalmoscopy it was

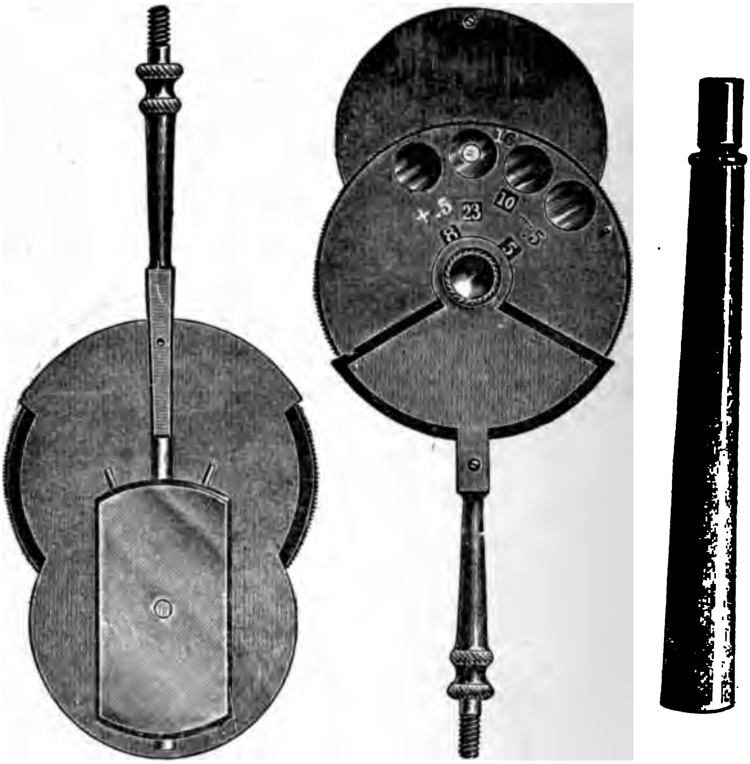

FIG. 89

Loring's Ophthalmoscope

The mirror is concave, shaped as in illustration, with a central perforation of 4 *mm* diameter, and so attached that it may be tilted to either side. The focusing lenses are contained in a full disk and a quadrant of a disk, the one revolving over the other, so that by suitable combination any lens required for neutralization of refractive error can be obtained.

shown that light reflected from the fundus of an emmetropic eye passes out of the eye in parallel rays, which may be brought to a focus on the retina of an emmetropic observer without exercise

of accommodation, so that there may be formed on his retina a clear image of the disk and blood vessels of the examined eye.

If the examined eye is *hyperopic*, light from its fundus leaves the eye in divergent pencils, and can be focused by an emmetropic observer only by the aid of accommodation, or by an equivalent convex spherical lens.

If the examined eye is *myopic*, the emergent pencils are con-

FIG. 90
Morton's Ophthalmoscope

In this instrument the lenses are set in a cylinder in the form of an endless chain, so that any required lens may be readily brought to the sight hole by means of the driving wheel.

vergent, and can be focused on the retina of an emmetropic observer only with the aid of a concave lens.

In applying this principle in practice we must in the first place be assured that no accommodation is exercised by the examining or the examined eye. The examiner must learn by previous practice to relax his accommodation at will; relaxation in the eye under examination usually occurs during ophthalmoscopic examination, provided it is conducted in a thoroughly darkened room.

These conditions being fulfilled, the examiner brings the ophthalmoscope and his eye as near as possible to the eye under examination. The ideal position would be such that the ophthalmoscopic lens would be 15 *mm* in front of the examined eye, the position at which trial lenses are placed in the subjective examination. So close an approximation is not possible, but we do not incur a noteworthy error by our failure to reach this position. The examiner now looks at the small vessels which lie on the outer side of the optic disk, tracing them as far as possible towards the macula, ***since it is the macular region whose refraction we wish to determine.*** The strongest convex or the weakest concave lens with which these vessels appear distinct measures the degree of ametropia if the examiner is emmetropic. When the latter is ametropic and his refractive error is not corrected the dioptric power of his correcting lens must be subtracted from that of the ophthalmoscopic lens with which the vessels appear distinct.

If +5 D is the strongest lens with which the retinal vessels are seen distinctly and if the examiner has 2 D of hyperopia, it is evident that 2 D of the ophthalmoscopic lens is required for the correction of the examiner's hyperopia, leaving 3 D as the degree of hyperopia in the examined eye. If the examiner has 2 D of myopia, while, as above +5 D is the power of the lens which makes the retinal vessels distinct, the hyperopia of the examined eye is 7 D. Subtracting —2 D, the lens-equivalent of the examiner's myopia, is the same as adding + 2 D. In other words, the examiner's myopia (2 D) neutralizes 2 D of the hyperopia of the examined eye, and this added to 5 D of hyperopia neutralized by the ophthalmoscopic lens, makes a total hyperopia of 7 D. Similarly, if the vessels appear distinct with —5 D, the examiner having 2 D of myopia, the myopia of the examined eye is 3 D; and if the examiner has 2 D of hyperopia, the vessels still being distinct with —5 D, the myopia of the examined eye is 7 D.

When the examiner has considerable astigmia, it is best

for him to have his correcting lens attached to the ophthalmoscope so that this lens may be used in combination with the spherical lenses of the instrument.

The same principle is applicable in the determination of astigmia; but in this case it will be noticed that when the vessels running in a certain direction appear distinct, those running in a direction at right angles to this will be blurred. *These two directions mark the principal meridians of the astigmia.* In accordance with the principles which we have learned, we know that the meridian in which the vessels are most blurred is that which is corrected by the ophthalmoscopic lens. After the number of this lens has been noted, the vessels at right angles to the first are next made to appear distinct. The difference between the power of the first and second lenses represents the degree of astigmia.

Much practice and skill are requisite for determining accurately the meridians and degree of astigmia by this method, and, as a practical test, it has been largely replaced by skiascopy and ophthalmometry.

Indirect Method of Ophthalmoscopy.—Since there is formed at the far-point of a myopic eye an aerial image of the optic disk and retinal vessels, the distance of this image from the eye furnishes a means of determining the degree of myopia. In emmetropic and hyperopic eyes the same method is applicable by adding a strong convex lens, as used in indirect ophthalmoscopy. This method, like many of the older tests, is not convenient in practical work, since it is not possible, without a special contrivance, to determine with precision the place at which the aerial image is formed.

Skiascopy.—This method is so simple in application and so accurate in results that it surpasses all other objective means of measuring refraction. *Bowman,* in 1859, first employed skiascopy for the detection of irregular astigmia in conical cornea. *Cuignet,* in 1876, introduced it as a test for all refractive errors under the name *keratoscopie.* The first explanations of the optical principles involved were given by *Landolt,* who suggested the name *pupilloscopie,* and by *Parent,* who adopted the name *retinoscopie.* The latter also introduced the practice of placing the correcting lens in front of the eye, thereby giving the test its practical value in estimating the degree of ametropia. The earlier names being mani-

festly unsuitable, *Priestly-Smith*, in 1884, recommended the term *shadow-test*, upon which is based the simple word *skiascopy*.

The necessary appliances for the application of skiascopy are a suitable lamp, a plane or concave mirror, and a set of trial lenses.* An Argand gas burner or a frosted electric lamp, mounted on an adjustable bracket, gives suitable illumination, or a miniature electric lamp may be attached directly to the mirror. The amount of light may be regulated by an opaque chimney having an opening in its side. The size of this opening should vary with the position of the light. When this is behind the patient, as is the case in the use of the concave mirror, the opening should be 2 *cm* or 3 *cm* in diameter; in fact, the opaque shade is in this case not essential. But when the light is in front of the patient and near the eye of the examiner, this being the most advantageous arrangement in the use of the plane mirror, the shade is indispensable, and the opening should not be more than 10 *mm* in diameter. Since we often wish to vary the position of the light relatively to the mirror, a convenient arrangement is a rotating disk, with openings of different sizes, any one of which may be used; or we may employ the iris-diaphragm, as in Thorington's adjustable diaphragm chimney (Fig. 91).

The *mirror*, being circular in form, should have at its center a circular sight-hole 2 *mm* in diameter; the mirror itself should be from 2 *cm* to 3 *cm* in diameter if plane, and somewhat larger (3 *cm* to 4 *cm*) if concave. The focal length of the concave mirror should be about 25 *cm*.

The *lenses* may be taken from the trial-case, any desired lens being supported in the trial-frame, and placed before the eye under examination; or, they may be arranged in a disk in such manner that any desired lens may be quickly brought before the eye.

The room in which the examination is made should be thoroughly darkened as for ophthalmoscopy, and if the pupil is small, cocain, euphthalmin, or homatropin should be used.†

The examinee and examiner are seated facing each other as for opthalmoscopy, the distance between the two being usually one meter. The examinee is instructed to look slightly to the right

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*A tape-measure for determining the distance between the patient and the observer is also useful.

†If the luminous (electrically lighted) skiascope is used, artificial dilation of the pupil is seldom required.

or left of the examiner's head, according as the right or left eye is under examination, while the examiner throws the light reflected from the lamp into the eye of the examinee. The examiner then, looking through the sight-hole of the mirror, perceives the light-reflex coming from the region between the optic disk and macula of the examined eye. Examination of the macular region is not possible because of annoying reflexes; but our aim should always be to have this region as little as possible removed from the line of vision, since the refraction of other parts of the eye sometimes

FIG. 91
Iris Diaphragm Chimney

differs materially from this portion, which alone is concerned in distinct vision.

The manner of measuring the ametropia by this method is best explained by means of illustrative examples.

Let us suppose, for instance, that with a plane mirror, held one meter from the eye under examination, the pupil appears brightly illuminated, and that on rotating the mirror the light reflex is followed by a slightly curved shadow which quickly covers the entire pupil. We know that we are near the point of reversal; that is, the eye has *about one diopter of myopia* (Fig. 92). If the rapidly moving shadow travels in the direction of rotation of the mirror, the myopia is slightly less than 1 D; if it travels in the opposite direction, the myopia is slightly in excess

of 1 D. By moving forward or backward we may find the position at which no appreciable shadow is observed, and by noting the distance from the eye the amount of myopia may be estimated. Or by adding a weak lens, convex or concave according as the direction of the shadow is with or against the direction of rotation, we select that lens which neutralizes the shadow movement. *The lens which produces this effect creates an artificial myopia of* 1 D.

If a *convex* lens of .50 D is required to produce this result, the eye, having 1 D of myopia with the lens, must have .50 D of myopia without the lens. If a *concave* lens of .50 D is required to neutralize the shadow movement the eye has without the lens 1.50 D of myopia.

When, on rotating the mirror in any direction, *the shadow moves slowly across the pupil in the direction of rotation of the mirror,* the reflex being dull, the eye is highly *hyperopic*. We place a 4 D convex lens before the eye, and note that the shadow moves more rapidly, but still in the direction of rotation. We substitute a convex lens of 6.50 D, and the shadow now moves rapidly in the direction opposite to the rotation. We therefore take a weaker lens (6 D) and find that there is now no appreciable shadow: hence, this lens produces 1 D of myopia, and the eye without the lens must have 5 D of hyperopia.

If the reflex is dull and moves slowly *in the opposite direction to the rotation*, the eye is highly *myopic*. We may estimate the degree of myopia roughly by moving towards the examinee until we reach the point of reversal. If this is one-tenth of a meter from the examined eye there exists 10 D of myopia; but as it is difficult to ascertain the exact point of reversal, and as a slight inaccuracy will make a difference of several diopters in high myopia, it is better to place before the eye a concave lens which will bring the point of reversal to a more convenient position, one meter from the eye. At this distance the error resulting from misjudging the exact point of reversal is slight. We, therefore, in this case place before the eye a concave spherical lens of 10 D and resume our former position, one meter from the eye. We notice that the *shadow moves with the rotation;* we substitute a weaker lens (9 D) and with this the shadow disappears. Since a concave lens of 9 D neutralizes all but 1 D of the myopia in this eye, the eye without the lens must have myopia of 10 D.

The next example is that in which the shadow moves with

the rotation in all meridians, but ***more rapidly in the vertical than in the horizontal meridian.*** By placing a convex spherical lens of 1 D before the eye the shadow is caused to disappear in the vertical meridian, but in the horizontal meridian the light and shadow still travel in the direction of rotation. The edge of the shadow will be straight, or nearly so (Fig. 93), and the direction of this edge *marks the direction of the axis of the cylindrical lens which corrects the astigmia.*

We now place before the eye, in addition to the 1 D sphere, a convex cylindrical lens of 2 D, axis vertical. With this lens no shadow is noticed in any meridian. Since the convex lens of 1 D is required to produce 1 D of myopia in the vertical meridian, the eye is emmetropic in this meridian. In the horizontal meridian the combined action of the spherical and cylindrical lenses is necessary to produce 1 D of myopia. The combined strength of these two lenses in the horizontal meridian is 3 D; in this meridian therefore there is 2 D of hyperopia without the lenses. There is in this eye *simple hyperopic astigmia* of 2 D.

FIG. 92

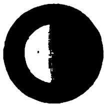

FIG. 93

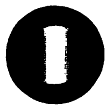

FIG. 94

FIG. 92.—Showing the form of the shadow in hyperopia, emmetropia, or myopia.
FIG. 93.—Showing the rectilinear shadow in astigmia when the examiner, being near the point of reversal of one principal meridian, tilts the mirror to one side.
FIG. 94.—Showing the central band of light in astigmia.

Further examples are unnecessary illustrating *compound astigmia* (both principal meridians being hyperopic or both myopic) and *mixed astigmia* (one principal meridian being hyperopic and the other myopic), since the method of procedure is the same in all cases. The point of reversal for one principal meridian is first brought to the position of the examiner with the aid of a spherical lens, and then by the addition of a proper cylindrical lens the point of reversal for the other principal meridian is brought to the same position.*

In the higher degrees of astigmia, and also in the lower degrees by exercising the proper precautions (p. 97), we may see the characteristic band of light (Fig. 94).

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*Or each meridian may be separately corrected by a spherical lens. The difference in power between the two lenses represents the astigmia.

The student who has mastered the principles of the test with the plane mirror will have no difficulty in the substitution of the *concave* mirror. As has already been explained, the movement of the light and shadow with the concave mirror is opposite to that with the plane mirror; that is, the motion is *against* the rotation of the mirror in *hyperopia* and *with* this rotation in *myopia*.

Another matter which must be remembered in the substitution of the concave for the plane mirror is that in the former the apparent source of illumination is the aërial image, situated in front of the mirror, whereas in the latter the apparent source of illumination is behind the mirror. With the concave mirror the aërial image cannot lie nearer the mirror than the principal focus, and with the approach of the lamp to the mirror the aërial image recedes from the mirror.

The ideal arrangement is such that the apparent source of illumination and the observer are at the same distance from the examined eye; and, at any rate, that the relation between these two is constant. With the plane mirror the apparent source of illumination may be brought near the observer by placing the lamp very near the mirror, the observer moving the lamp as he moves his position; or he may have a miniature electric lamp attached to the mirror. Hence, with the *plane mirror* the examiner may vary his position at his convenience. He may thus *estimate the ametropia with few changes of lenses.* But when the *concave mirror* is used, alterations in the illumination of the pupil, due to the variation in position of the aërial image, are so great as to render the test unsatisfactory unless the observer selects a fixed position for himself and the lamp. The lamp should be behind and he should be one meter in front of the examinee.

Difficulties in the Application of Skiascopy.—Although the phenomena of skiascopy are characteristic, yet when we come to employ this method of examination in practice, we frequently meet with difficulties which arise from imperfections in the optical construction of the eye.

The chief disturbing element is *aberration.* Since in normal eyes the refracting surfaces are approximately portions of spherical surfaces, the light which passes near the center of the pupil is less highly refracted than that which passes along the

periphery. Hence, when the examiner is at the point of reversal for the central area, he will be without that for the peripheral part of the widely dilated pupil. If the aberration is abnormally great, he may see clearly the shadow at the periphery move in one direction, while that at the center moves in the opposite direction. As the central area is the part concerned in normal vision, the examiner should ascertain the point of reversal for this part of the pupil, disregarding the movement at the periphery.

The aberration just described is ordinary spherical or *positive* aberration; it is the form which usually occurs in the eye. But the opposite or *negative* aberration sometimes occurs. This is the rule in *conical cornea,* for in this condition the curvature of the cornea is much greater at the center than at the periphery.

It was the effect of aberration in conical cornea that attracted the attention of *Bowman.* When in this affection the observer is at the point of reversal for the periphery he will be far removed from this point for the center of the pupil. The shadow at the center will therefore move slowly while that at the periphery will move rapidly, presenting the appearance of a central light area encircled by a swiftly moving peripheral shadow.

Another difficulty in the application of skiascopy is that which arises from *irregular astigmia.* This exists, to a certain extent, in all eyes. A careful observation of the shadow when the examiner is near the point of reversal will reveal this by the faint conflicting shadows moving in various directions. When the irregular astigmia is more pronounced, these shadows are so marked as to interfere seriously with the estimation of the refraction at the center of the pupil. This is especially so in eyes whose corneas have been the seat of inflammation or ulceration, whereby the regularity of surface has been destroyed. There is no one point of reversal for such eyes, and distinct vision is not obtainable.

A peculiar appearance, described by *Jackson* as the *scissors movement,* is sometimes seen. This movement appears when in any direction the eye is more highly refracting in one-half of the pupillary area than in the other half. Thus, if the examiner is within the point of reversal for the upper part of the pupil and without this point for the lower part, rotation of the mirror will cause the two shadows to move towards or away from the center of the pupil. Since the appearance resembles the opening and shutting of a pair of scissors, it has received therefrom its name.

In order to obtain a clear conception of these various appearances and to obtain the requisite skill for the practical application of skiascopy, the student should procure a *skiascopic eye* (Fig. 95), constructed for this purpose, and thoroughly familiarize himself with the phenomena which are to be observed in various grades of ametropia. Having accomplished this, he is prepared to make further studies upon living eyes, selecting at first those which are free from marked irregularities. He should, if possible, conduct the examination with a moderately dilated pupil, so as to avoid the aberration and irregular astigmia commonly present at the periphery when the pupil is widely dilated.

Ophthalmometry.—Ophthalmometry, in the commonly accepted meaning of the word, consists in determining the corneal astigmia by direct measurement of the corneal curvature.

When there is a very decided asymmetry or irregularity of the cornea, it may be detected with *Placido's disk* (Fig. 96), which consists of a series of concentric circular rings painted on a metal disk having a hole in the center. The observer, looking through this hole, reflects light from the disk to the cornea under examination while he observes the reflected image of the rings as formed at the anterior surface of the cornea. In marked

FIG. 95
Eye Model for the Practice of Skiascopy

regular astigmia the image of the rings appears *oval,* and in *irregular astigmia* the image is *distorted.*

But for the accurate measurement of the cornea the ophthalmometer is used. (Fig. 97.) The principle on which this instrument is constructed has already been described in Part I.

In the application of ophthalmometry the person to be examined, being properly seated before the instrument, the forehead supported in the frame provided for that purpose,

FIG. 96
Placido's Disk

and the eye not under examination being covered by the blind attached to the head-rest, the operator adjusts the tube of the telescope while the examinee looks directly into the tube, taking care to keep the eye wide open, the two eyes on a level, and the forehead firmly resting in the frame. The operator then looking through the telescope sees the double images of the mires reflected from the cornea. If these are blurred, they are brought into focus by proper adjustment of the telescope. The instrument is then still further adjusted vertically or horizontally so that the two inner images are brought into the center of the field of view, the two lateral images being disregarded. After this is accomplished the instrument is revolved until the axial lines of the images show a single straight and unbroken line. If there is no corneal astigmia this condition will exist in all meridians; otherwise in only two meridians—the principal meridians of the cornea, or the *axes of the astigmia.*

An axis having been thus ascertained, the ***primary position*** (Fig. 98) is obtained by appropriate adjustment and the corneal refraction (in diopters) is noted. The tube and mires are next rotated, and the departure from the axial position is indicated in an asymmetrical cornea by a break in the axial lines.

When the rotation has been carried through 90° the axial lines are again continuous.* If in this, the secondary position, there is an overlapping of the mires (Fig. 99), the astigmia may

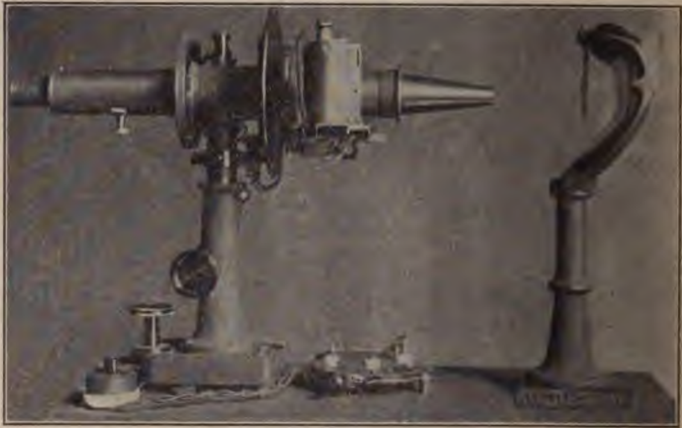

FIG. 97

The ophthalmometer as adapted for measuring both corneal and lenticular astigmia.

be measured by the amount of overlapping (*Javal-Schiötz*), or the images may be again brought into the contact position and the astigmia measured by noting the difference in reading of the scale in the two meridians. If in the secondary position there is a separation of the mires, they should be brought into the contact position and the reading noted, or, after obtaining the contact position, the instrument may be revolved into the first found meridian, when there will be an overlapping of the mires.

If the first meridian is horizontal or nearly so, while the mires overlap in the vertical meridian, the astigmia is *with the rule* (*direct*), and if the mires are separated in the vertical meridian the astigmia is *against the rule* (*indirect*).

*As the curvature of the cornea lacks mathematical accuracy, the two meridians are not always exactly at right angles, but their deviation from this relation is very slight.

In the use of the ophthalmometer it is essential that the eye under examination be maintained in a fixed position during the process of measurement, for the result is of little value if this precaution is not taken. We should be assured that we are measuring the curvature in the pupillary area.

There are several reasons why the ophthalmometric record frequently fails to agree with the subjective astigmia. One cause

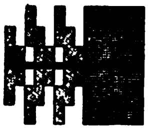

FIG. 98
Primary Position.

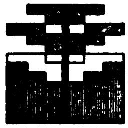

FIG. 99
Secondary Position—overlapping of the mires.

for this disagreement is the lack of care in making the measurements under the precautions just mentioned. In fact, without more cooperation than some patients are able to give, a reliable ophthalmometric reading is impossible.

Another cause for this disagreement is that we measure a very small part of the pupillary area of the cornea, while in other portions of this area the curvature differs from that which we measure.

The refractive effect of the posterior surface of the cornea is also an uncertain factor; but if this surface follows the conformation of the anterior surface, as is probable, there is no appreciable error from the neglect of this refraction.

Disappointment in the use of the ophthalmometer is also due *to the failure on the part of the examiner to bear in mind that there is in high degrees of symmetrical ametropia* a wide variance *between the astigmia as measured at the corneal surface and its correcting lens placed at a distance of 15 mm from the cornea.* The explanation of this discrepancy will be found in the appendix.

Finally the disagreement between the subjective astigmia and the keratometric record may be due to *asymmetry of the crystalline lens.*

In the application of keratometry we are taught to deduct .50 D from the corneal astigmia if this has its meridian of

greatest refraction vertical, and to add this amount if the meridian of greatest refraction is horizontal. The reason usually given for this empirical rule is that the obliquity of the crystalline lens produces .50 D of astigmia with its meridian of greatest refraction lying in or near the horizontal plane. In order that this amount of asymmetry may be effected by the oblique position of the lens, the angle alpha must be about ten degrees, whereas it is usually not more than five degrees. This amount of obliquity produces a little more than one-eighth of a diopter of astigmia. We must therefore look elsewhere for the common discrepancy of .50 D between the keratometric record and the subjective astigmia.

In the application of my ophthalmometer I have found that this discrepancy is almost always due to asymmetry of the posterior surface of the lens. Not infrequently the astigmia of this surface reaches 1 D, or even more. In other instances the surface is symmetrical. We cannot therefore formulate any general rule as to the amount of the crystalline astigmia which is to be added to or subtracted from the keratometric record.

Owing to the larger radius of the anterior surface of the lens a high degree of asymmetry is required to produce an appreciable amount of astigmia. The highest amount which I have measured is .75 D. In the large majority of cases the amount is less than .25 D.

In the measurement of the anterior surface of the lens the eye must be under the influence of a mydriatic (a cycloplegic in young persons), but this is not necessary in the case of the posterior surface.

In view of the difficulties and uncertainties of ophthalmometry many ophthalmologists think that this method of examination has so little practical value that it does not repay the examiner for the time expended in its application. My own opinion, however, is, that if used with a proper appreciation of its limitations, *keratometry* is of great value; furthermore, I believe that *phakometry,* at least of the posterior surface, is worth the time which it requires, in that it often affords an explanation of optical conditions which would otherwise remain unsolved.

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CHAPTER XI

HYPEROPIA

Hyperopia (*H*) is that condition in which, when the ciliary muscle is in a state of relaxation, the retina intersects the axis of the optical system of the eye in front of the posterior principal focus of this system, or it is that condition in which the antero-posterior diameter of the eyeball is too short in relation to the position of the posterior focus (p. 61).

Prior to the investigations of *Donders* hyperopia was confused with presbyopia, and it was called hyper-presbyopia. It was thought that the eyes of young persons whose vision was improved by convex lenses had grown prematurely old. It was also commonly believed that it was very injurious for such persons to wear correcting glasses. Thus an immense amount of suffering and of serious injury to the eyesight was needlessly endured. We are therefore greatly indebted to Donders for the boon which he bestowed upon humanity in the elucidation of this subject.

Donders called this condition of refraction *hypermetropia,** a term which is the analogue of emmetropia. The word which is now more commonly used, *hyperopia,* has the advantage of being shorter; it also corresponds to the common expression, *far-sightedness.*

The hyperopic state of refraction of itself reveals to us nothing as regards the curvatures of the surfaces, the indices of the media, or the size of the eyeball. It indicates only that there is a disproportion between these various factors, in which the eyeball is relatively too short. If the length of axis and the indices of the media approximate closely to the average which numerous investigations have established as the standard for the human eye, while the curvature of one or more of the surfaces is perceptibly less than the average, the resulting hyperopia is assigned to deficiency of curvature and is called ***curvature-hyperopia.***

* From ὑπέρ μέτρον beyond measure, and ὤψ sight.

When the curvatures and the length of axis are normal, with a deviation from the average in one or more of the indices, any resulting hyperopia is called *index-hyperopia;* and when the curvatures and indices are normal, the hyperopia is attributable to deficiency in length of axis, and is called *axial hyperopia.*

Curvature-Hyperopia

Curvature-hyperopia is not common. Ophthalmometry shows us that ordinarily in hyperopia the curvature of the cornea and of the lens is not below the average, although exceptionally the radius of the cornea may so much exceed the standard as to produce hyperopia in an eye of normal length.

The hyperopia which exists in aphakia, since it is due to absence of the lenticular curvature, may be regarded as curvature-hyperopia.

Index-Hyperopia

The refractive index of the aqueous and vitreous has been found so nearly constant in health that we are justified only under exceptional circumstances in ascribing hyperopia to abnormal index of these media.

If the density of these two media should be increased, as from the presence of sugar, a condition of hyperopia would result, for the increase of convergent refraction, which would occur at the cornea would be overbalanced by the diminution in the refraction by the crystalline lens. In this way has been explained the hyperopia which has occasionally been observed to develop in diabetes.

Index-hyperopia may also occur from the equalization of the refractive index throughout the lens, as usually takes place with increase of age. As the density of the outer layers of the lens approximates that of the nucleus, the refractive power is diminished and hyperopia may result.

Hyperopia due to the absence of the crystalline lens, which has been classed as a curvature defect, may with equal propriety be regarded as index-hyperopia, for in this condition the total index of the eye is abnormally low.

Axial Hyperopia

Occasionally axial hyperopia occurs from pathological displacement of the retina, as in partial detachment; but ordinarily

it is due to congenital deficiency in the antero-posterior diameter of the eye as compared with the average normal diameter. This is the typical form of hyperopia, and to it we assign all cases unless there is positive evidence that the defect is due to other cause. We must not forget, however, that in the lowest grades of hyperopia this is an arbitrary distinction, for an extremely slight variation in axial length—such as occurs in emmetropia—will effect a refractive change of several diopters, unless accompanied by suitable adaptation of curvature or index.

The method of determining the deficiency in length of axis was demonstrated in Part I (p. 80). In the manner there described the following table has been constructed, indicating the length of axis and the deficiency in various grades of hyperopia as measured by the correcting lens placed at the anterior focus of the eye.

Hyperopia	Length of Axis	Deficiency
0 D (Emmetropia)	23.2 *mm*	
1 D	22.9 "	0.3 *mm*
3 D	22.2 "	1.0 "
5 D	21.5 "	1.7 "
7 D	20.9 "	2.3 "
9 D	20.2 "	3.0 "
11 D	19.5 "	3.7 "
13 D	18.9 "	4.3 "
15 D	18.2 "	5.0 "

From this table we see that a shortening of 1 *mm* in the antero-posterior diameter of the eye corresponds to hyperopia of 3 D; but this amount of shortening is by no means incompatible with emmetropia, and therefore there is no demonstrable deficiency in length of axis in the lower grades of hyperopia.

If emmetropia is regarded as the normal state of the human eye, the axially hyperopic eye must be regarded as an eye which has not attained perfect development. In this respect such eyes resemble those of the lower animals and of children, in whom hyperopia is the normal condition.

A large number of examinations has revealed an average of about 3 D of hyperopia in newborn children. This, however, does not correspond to an antero-posterior diameter of 22.2 *mm*, as it would in an adult. The average length of axis in the newborn is about 17 *mm*, for the curvature of the cornea and of the crystalline lens is greater than it is in the adult. There is a very rapid change in this respect, however, and it is said that after

the third year the corneal curvature does not ordinarily undergo any material change.

As age advances the eye increases in size, with a gradual diminution of hyperopia, which normally passes into a condition approximating emmetropia about the twelfth or fifteenth year. The proportion of eyes which reach the emmetropic state varies with the communal habits, since the eye in a measure adapts itself to the predominating requirements. The proportion may be approximately estimated as one-half in adults.

In consequence of the irritation to which the eye is subjected during school life, and in some cases because of inherent weakness of the sclera, the enlargement of the eyeball is frequently not arrested when emmetropia is attained, and this further increase in the antero-posterior diameter gives rise to myopia. It is fortunate, therefore, that this tendency is counteracted by the natural state of hyperopia.

In savage races, in whom the influences tending to cause axial elongation have not been brought into action, the normal condition, even in adult life, is that of hyperopia.

The eyes of congenitally deaf persons are also usually hyperopic, and not infrequently to a very high degree. The cause to which is due the arrest of development of the auditory apparatus affects also the eye.

Degree of Hyperopia

Hyperopia varies in degree from a condition imperceptibly differing from emmetropia, on the one hand, to microphthalmos, on the other. In the former case, therefore, it is limited by the accuracy of our means of diagnosis. In the earlier days of ophthalmology eyes having hyperopia not exceeding 1 D were regarded as emmetropic; but now it is customary to measure .25 D, or even .12 D, of refractive error. In doing this, however, one must not forget that an eye which at six meters, or less, *accepts* (without detriment to vision) a convex lens not exceeding .12 D or .25 D, is more nearly adapted for distant vision without the lens than with it.

When the hyperopia reaches such a degree that the eye may be considered microphthalmic, the refractive error becomes a secondary matter, since defects in development of the media and of the nervous elements usually outweigh in importance the optical

defect. Hyperopia exceeding 14 D or 15 D does not occur (except in aphakia) in eyes which possess useful vision; in fact, an amount exceeding 8 D or 10 D is seldom encountered.

Low-Grade Hyperopia.—Under this heading we include all cases of hyperopia in which the error is less than 3 D. Eyes possessed of such a degree of hyperopia are in their anatomical structure and in their physiological workings not inferior to emmetropic eyes as long as there is sufficient accommodative power to overcome the refractive error without undue nervous strain. Such eyes may, therefore, be regarded as normal, except that in the process of growth there has occurred a disproportion between the curvatures and the length of axis.

There is, however, no ground for the prevalent belief that the visual acuity of far-sighted eyes surpasses that of the normal emmetropic eye. It is true that the savage or the hyperopic frontiersman, or the sailor, may be able to distinguish a distant object which cannot be seen by a town dweller, but this is because the former has by familiarity learned to analyze images which escape the attention of the latter.

Medium Hyperopia.—This class embraces those cases which are not less than 3 D and not more than 5 D. In such eyes there is usually an appreciable deficiency in the axial length. This is rendered apparent by turning the eye strongly to the nasal or to the temporal side, when there will be revealed an abnormally great curvature at the equatorial region of the eyeball, the appearance thus differing from that presented by the emmetropic or, to a still greater degree, by the myopic eye.

It is not only the eyeball that presents this characteristic appearance. The conformation of the face and cranium also frequently exhibits a flattened aspect. The bridge of the nose, the forehead, and the orbital borders all lack the relief that is present in more fully developed skulls. This lack of development of the bones of the face occurring with imperfect development of the eye is very noticeable in certain cases of asymmetry of the face, the eye on the side of inferior development being smaller than that on the other side. There are, however, many exceptions to this concurrence, for equal refraction in the two eyes is not uncommon in asymmetry of the face, and *vice versa*.

High-Grade Hyperopia.—This class embraces all cases of hyperopia which exceed 5 D. In such cases the smallness of

the eye is not confined to the antero-posterior diameter; the eye is noticeably small in all its dimensions. With this deficiency in size the curvature of the cornea and lens is not infrequently abnormally great. This type of eye is illustrated diagrammatically in Fig. 100.

The imperfect development in this grade of hyperopia often extends to the nervous mechanism—as characterized by pallor

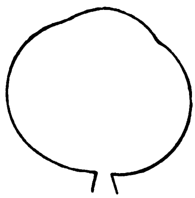

FIG. 100
The Hyperopic Eye.

and irregularity of outline of the optic disk, or, at times, by increased redness, simulating neuritis. In such cases normal visual acuity is not attained after correction of the refractive error.

Latent and Manifest Hyperopia

A part or the whole of the hyperopia of an eye may be overcome by involuntary contraction of the ciliary muscle. Hyperopia so overcome is said to be *latent* (*Hl*). The existence of latent hyperopia can be ascertained only by ophthalmoscopic examination in a darkened room, or by paralysis of the ciliary muscle by means of a cycloplegic.

When the ciliary muscle relaxes to some extent so that a certain portion of the compensating accommodation may be replaced by a convex lens, the strength of this lens represents the *manifest* hyperopia (*Hm*). The sum of the manifest and latent hyperopia constitutes the *total* hyperopia (*Ht*).

The proportion of total hyperopia which remains latent varies in individuals and at different ages. From complete latency so often found in childhood, a gradually increasing portion becomes manifest with the weakening of accommodative power, so that in old age the total hyperopia is manifest.

Manifest hyperopia may be either *facultative* (*Hf*) or *absolute* (*Ha*). A hyperope of 3 D may have normal distant vision without any correcting lens; if he still has normal vision with a convex lens of 1 D, while any stronger lens blurs vision he has 1 D of *manifest* and 2 D of *latent* hyperopia. Since he is able by exercise of his accommodation to overcome the manifest hyperopia, the latter is said to be *facultative*. But when this same person is fifty-two or fifty-three years of age he has at his disposal only about 2 D of accommodation. At this age the total hyperopia will be manifest, but only 2 D of this manifest hyperopia can be overcome by accommodative action. He has, therefore, 2 D of facultative and 1 D of absolute hyperopia.

Symptoms of Hyperopia

The subjective symptoms of hyperopia vary with the degree of the defect, with the accommodative power, and with the occupation and nervous irritability of the individual. Hence, we must not be surprised to find slight hyperopia causing very great annoyance in one person, while a much higher degree in another person may cause no disturbance whatever.

Vision in Hyperopia.—As long as there is sufficient accommodative power to overcome the error vision is unimpaired. Hence in slight hyperopia distant vision may be normal until an advanced age, and near vision may be affected only in that reading glasses are required at a slightly earlier age than in emmetropia. But when the hyperopia reaches the medium degree near vision becomes burdensome in early adult life, and distant vision also becomes subnormal before middle age. Thus a hyperope of 4 D, when he reaches the age of forty years, has only 4.5 D of accommodation, leaving only .50 D in reserve after adapting his eye for distant vision. He could not, therefore, maintain normal distant vision for more than a brief period, and near work, such as reading ordinary print, would clearly be impossible.

In the highest grades of hyperopia vision falls below normal at a still earlier age, and distant vision may be defective in childhood, even though there may be no arrest of development of the nervous mechanism.

Owing to insufficiency of accommodation in low and medium hyperopia there is a tendency for the person, as he grows older,

to hold his book or other work at an abnormally great distance. On the other hand, in the highest grades of hyperopia distinct images for near work are not possible even in childhood, and the child, learning this, abandons the attempt to secure distinctness, and instead obtains larger images by holding his work very near the eyes, thus leading the casual observer to the erroneous conclusion that the child is near-sighted.

Defective vision may also arise in hyperopia from abnormal weakness of the ciliary muscle, such as occurs from exhausting diseases, or from paralysis of the third nerve, as in diphtheria.

Asthenopia.—This term is used to designate a group of symptoms characterized by pain in and about the eyes and in the frontal region, extending at times beyond the temples and even as far as the occiput and nape of the neck. These disturbances are produced by close application of the eyes, which tire easily. After short use of the eyes the print becomes blurred or unsteady, and pain, accompanied at times by photophobia, redness and watering of the eyes, becomes so great that cessation from work is imperative. After a period of rest the symptoms disappear, but upon resumption of work they recur with aggravated intensity. Asthenopia (*eye-strain*) sometimes gives rise to nausea, or to vertigo, and less commonly to insomnia, mental depression, nervous prostration (so called), and, according to some ophthalmologists, to chorea, epilepsy, and other reflex disturbances.

Asthenopia may result from any one of several causes.

(1) *Hysterical, nervous,* or *retinal asthenopia* occurs in hysterical and neurasthenic persons as a manifestation of nerve-exhaustion, and it occurs not infrequently in eyes which are apparently normal.

(2) *Muscular asthenopia* results from muscular imbalance, which necessitates an abnormal strain to preserve binocular vision. Since the normal relation between accommodation and convergence is disturbed in hyperopia, it might be inferred that muscular asthenopia would be a common symptom in this affection; but, since hyperopia is congenital, the relation between convergence and accommodation may become adapted to the hyperopic condition; in other cases binocular vision is abandoned at an early age, when the incentive to it is slight, and the unused eye passes into a state of strabismus.

(3) *Accommodative asthenopia* results from overuse of the ciliary muscle, and since this muscle has the greatest tax thrown upon it in the hyperopic state of refraction, accommodative asthenopia is pre-eminently the asthenopia of hyperopic eyes.

Headache.—This has been mentioned as being one of the manifestations of asthenopia, but it sometimes occurs without any symptoms directly referable to the eyes. Ocular headache may consist in a dull pain in the forehead, supra-orbital neuralgia, occipital pain, usually combined with frontal headache, or severe migraine or sick headache. Pain at the vertex is sometimes, though more rarely, attributable to eye-strain.

Objective Symptoms.—The characteristic form of the face and of the eyeball has been mentioned in the present chapter. In addition to these indications there are not infrequently found marginal blepharitis, conjunctival congestion or inflammation, or epiphora, and sometimes, from prolonged eye-strain, congestion and haziness of the retina in the region of the optic disk are observed upon ophthalmoscopic examination; but these symptoms are not pathognomonic. Such symptoms as may be so regarded have been fully considered under the head of objective methods of determining the refractive condition. (Chapter X.)

Strabismus.—In hyperopia distinct images are obtained in near vision only through an abnormally great effort of accommodation, and this excess of accommodation is accompanied by a correspondingly great innervation of convergence. If the desire for binocular vision predominates, the excess of convergence will be overcome, either by the acceptance of blurred images, with less accommodation, or by maintaining the muscular balance at the expense of undue nervous energy. But if the incentive to binocular vision is outweighed by the other factors, one eye will be used for vision while the other assumes a position of excessive convergence. This constitutes *internal* or *convergent strabismus.* Hence, anything which weakens the natural impulse for binocular vision facilitates the occurrence of strabismus. This defect frequently appears therefore after loss or diminution of sight in one eye, or when one eye is congenitally defective, or if the refractive condition is unlike in the two eyes.

The strabismus which may be assigned to hyperopia as the chief causal factor usually occurs at an early age (in the second

or third year), when the habit of binocular vision has not become strongly fixed and when the secondary image, falling upon a peripheral portion of the retina, seems to attract no attention. Sometimes the onset of the strabismus is delayed until the beginning of school-life, and its occurrence may be due to debilitating illness, as measles, scarlet fever, or diphtheria. In consequence of the weakness of accommodation following such diseases, a greater effort is required to secure the proper action of the ciliary muscle than in health, and this excessive effort often produces excessive convergence.

Convergent strabismus occurs most frequently in medium degrees of hyperopia. In the lower grades the relation between the two functions of accommodation and convergence usually becomes adapted to the altered conditions, provided there is normal incentive to binocular vision. In the highest degrees of hyperopia distinct images in near work are impossible, and the effort to secure them is not attempted. In such cases there may be binocular vision with indistinct images in both eyes, or binocular vision may be abandoned, the work being brought very near the eye for the sake of enlarged images. In the latter case, since there is no attempt to form distinct images with the aid of accommodation, there is no incentive to convergence, and the unused eye may fall into a state of divergence. In this way is produced the *divergent strabismus* which sometimes occurs in high degrees of hyperopia.

The foregoing explanation of the causal relation between hyperopia and convergent strabismus was given by *Donders,* but he erred in believing that hyperopia was the most important factor in the etiology of the strabismus. Many recent authorities go too far the other way and hold that hyperopia has no etiological connection with strabismus. While a deficiency in the normal impulse for binocular vision is doubtless the most potent factor, the presence of hyperopia acts as a very powerful predisposing cause of strabismus, and the correction of this defect often enables the eyes to assume their normal function of binocular vision.

Diagnosis of Hyperopia

Hyperopia may be suspected from the presence of some or all of the above-mentioned symptoms, but its existence is demonstrated and its degree measured by means of the subjective and

objective tests considered in Chapter X. In the routine examination for the determination of refractive error the objective examination is usually conducted first (or after a short preliminary subjective examination) beginning with ophthalmometry. Ophthalmometry is useful in hyperopia only in so far as it reveals the coexistence or absence of astigmia.

After completion of the ophthalmometric examination skiascopy is next in order. The indications for the employment of a cycloplegic in this test are the same as in the subjective examination with trial lenses.

Owing to the greater accuracy of skiascopy, ophthalmoscopy is no longer used in the final measurement of refractive error, but it is valuable in that it enables the examiner to note the condition of the media and of the fundus.

In strabismus and in high hyperopia it is often necessary to correct the error before the child is old enough to submit to the subjective examination. In such cases reliance must be placed upon ophthalmoscopy and skiascopy with cycloplegia.

After the completion of the objective examination the subjective test with trial lenses is undertaken.

In regard to the advisability of using a cycloplegic for the determination of hyperopia ophthalmologists are not all of the same opinion. Some believe that latent hyperopia does not require correction, and that by exercise of proper care, as by the fogging method, all of the relaxable accommodation may be discovered without the use of any drug. I believe that without resorting to cycloplegia the experienced refractionist may in quite a large proportion of young persons prescribe glasses which will bring relief from asthenopia. There is, however, always an uncertainty as to the amount of latent error; and not infrequently the strength of the glasses must be increased at short intervals to keep pace with the continual increase of the manifest error.

The employment of a cycloplegic has, therefore. the great advantage of enabling us to derive certain knowledge of the true static refraction and of the behavior of the ciliary muscle. On this account it is better to paralyze the accommodation before attempting to make an accurate estimate of the refractive error of a child or young adult.

As the age of the patient increases the necessity of using a

cycloplegic becomes less imperative. In my opinion it is not, as a rule, required after the age of thirty years. Its use may, under favorable conditions, be dispensed with prior to this age, and it may in other cases be required at a greater age. In the choice of a cycloplegic the tendency among ophthalmologists is more and more to rely upon *homatropin* in ordinary routine work, and to reserve the long-persisting cycloplegics, such as atropin, for cases of strabismus and spasm of the accommodation.

When a cycloplegic is used the eyes should be protected from an excess of light by dark or amber-tinted glasses until the mydriasis disappears.

After the age of forty years a cycloplegic should not be used until it has been ascertained that the patient has no tendency to glaucoma, as disastrous results have occurred from lack of this precaution.

Treatment of Hyperopia

The degree of hyperopia having been ascertained, in accordance with the preceding directions, it is our duty to prescribe such lenses as will afford the eyes, if possible, their normal or physiological working power.

While some ophthalmologists maintain that latent hyperopia does not require correction, others believe that the eyes should in every case be placed in a condition of emmetropia by means of lenses which correct any deviation from this ideal condition. Neither of these plans should be blindly followed. It is impossible, to formulate a general rule, for each case must be judged in accordance with the symptoms and attendant circumstances. While the measurement of refractive error is in most cases a simple procedure, the prescribing of proper lenses is a far more difficult matter, which requires much thought and care. All that may profitably be formulated is an outline of the method usually to be pursued; we must leave to the judgment of the reader the modifications to be made in practical work.

Correction of Low-Grade Hyperopia in Childhood.— It is not probable that hyperopia of .50 D or .75 D is capable of causing asthenopia or other disturbance in a healthy child who has at his disposal 10 D or 12 D of accommodation. In those children in whom the correction of so slight an error

brings relief, it is likely that the beneficial result is due to psychic influence, and not to the aid which the lenses give to the accommodation. That many children desire to wear glasses for egotistical reasons is unquestionable. But since such influences are not unimportant in the production of subjective symptoms, it may perhaps occasionally be proper to prescribe weak lenses in cases of this kind, with the instruction that they are to be worn only for near work, and with the statement also, in the presence of the child, that a cure will be effected in a short time. In almost all these cases the symptoms will be relieved and the glasses discarded in the course of a few months.

On the other hand, it must be borne in mind that while hyperopia is the natural condition in childhood, the school-life of the child of modern civilization is artificial, and it may well be that the accommodation which is ample for a life in accordance with nature is insufficient, even in a moderate degree of hyperopia, to stand the strain of near work entailed by school duties. In such cases glasses should be ordered for school use and for reading. A portion only of the hyperopia should be corrected, because total correction would entail defective distant vision,—a manifest disadvantage in school work. As a rule, not more than one-half or two-thirds of the total correction can be comfortably worn before the age of fifteen years.

Correction of Low-Grade Hyperopia in Adult Life.— Low-grade hyperopia which has passed unnoticed in childhood requires correction sooner or later in the adult. The age at which correction becomes necessary varies with the amount of error and with the health and occupation of the individual. As a rule, relief will be sought early by accountants and others engaged in exacting near work. If the hyperopia is latent, and especially if it is slight (not more than 1 D), the use of glasses in near work will ordinarily suffice. On the other hand, manifest hyperopia is an indication for the constant use of glasses. In some cases, however, and especially in elderly persons who are not engaged in exacting work, correction for near use only is required.

When correction of the manifest error, required for constant wear, is insufficient for near work, it may be necessary to order two pairs of glasses, the manifest correction for distance, and the total correction for near work; but ordinarily a judicious

selection of a single pair for all purposes will afford relief until the onset of presbyopia.

Correction of Medium and High-Grade Hyperopia.—A medium grade of hyperopia may pass unnoticed throughout childhood; but usually, and especially in town life, it will give rise to asthenopia early in the school career. In the correction of hyperopia reaching a medium degree glasses must be worn constantly, as a rule, even in childhood, for the proper relaxation of the ciliary muscle can be obtained only by prolonged training with the use of the correcting lenses; moreover, a fixed relation between accommodation and convergence cannot be established unless the glasses are worn constantly. The proportion of the hyperopia to be corrected varies with the age and with other circumstances, in accordance with which the examiner must judge as to the proper lenses to be prescribed.

Similarly, *high-grade hyperopia* requires correction at an early age—at or before the beginning of the school career.

Treatment of Muscular Disturbances.—Muscular asthenopia or strabismus, in so far as either of these affections may be directly due to hyperopia, requires only the treatment appropriate for the causal refractive error; but the concurrence of muscular disturbance is a factor which must be considered in the prescription of correcting lenses. Even in mild hyperopia, in which during childhood correction for near work might otherwise suffice, it would be imperative that glasses should be worn constantly if the hyperopia should be complicated by strabismus; furthermore, it would not be advisable, as previously recommended, to leave any considerable part of the latent hyperopia uncorrected.

Whereas in uncomplicated hyperopia correction is not often called for before the school age, the occurrence of strabismus requires correction of the hyperopia at the earliest age compatible with the wearing of glasses—usually between the second and third year.

When muscular disturbance which may have been originally produced by hyperopia has become so fixed through neglect that correction of the hyperopia does not restore the proper muscular balance, resort must then be had to other measures. These will be considered in a subsequent chapter.

Secondary Effects of Convex Lenses

In the application of lenses to the correction of hyperopia, there are certain secondary effects which not infrequently create confusion until the eyes become accustomed to the altered conditions.

Enlargement of the Retinal Image.—We have learned in Part I (p. 79) that the retinal image in unaided axial hyperopia is slightly smaller than in emmetropia; that the correcting lens exerts a magnifying effect upon this image, such that if the lens is placed at the anterior focus of the eye, the resulting image is of the same size as that of the emmetropic eye; and that if the lens is farther from the eye than the anterior focus, the image is larger than that of the emmetropic eye. Since spectacle-lenses are usually of low power as compared with the refractive action of the eye, and since, although worn without the anterior focus, they are yet very near this point, the retinal image in corrected axial hyperopia does not materially differ from that in emmetropia. Hence, when a hyperope replaces his overstrained accommodation by convex lenses his retinal images are slightly larger than those to which he has been accustomed.

In the curvature-hyperopia of aphakia the correcting lens is placed within the anterior focus of the aphakic eye, and the effect of the lens is to reduce the size of images, yet they are materially larger than in emmetropia and, consequently, larger than they were before removal of the crystalline lens.

Apparent Magnification of Objects.—Of greater importance than the actual change in the retinal image is the apparent enlargement produced by convex lenses—an effect which is due entirely to psychic influence. No knowledge as to the size of an object is revealed by the size of the retinal image alone. It is the size of this image taken in conjunction with the estimated distance by which we form a correct judgment as to the dimensions of an object.

The estimation of distance and size is a complex mental act, based upon previous experience and association of muscular actions. In this act the degree of accommodation and convergence exercised, the movements of the eyes required to fix every part of the object, and the knowledge as to the actual size of the object are all important contributing factors.

Convex lenses, by diminishing the amount of accommodation required to see an object distinctly, lead one to suppose that the object is more remote than it actually is, and, consequently, they make the object appear larger than it is as seen with the naked eye. On this account objects usually appear abnormally large to the hyperope when he begins to wear correcting lenses, even though the actual enlargement of the retinal images may be negligible.

Alteration in the Relation between Convergence and Accommodation.—In uncomplicated hyperopia a certain convergence is accompanied by a greater amount of accommodation than in emmetropia; hence, when correcting lenses are worn the associated nerve centers must be trained to modify this relation so that it will conform to the emmetropic standard. This is a common cause of disturbance when glasses are first worn.

When, on the other hand, hyperopia is accompanied by excessive convergence, the restoration of the normal relation between convergence and accommodation is one of the benefits bestowed by the correcting lenses.

Prismatic Action of Convex Lenses.—When the optical center of a lens lies in the line of vision the object seen undergoes no lateral displacement; but when an object is viewed through an eccentric portion of a lens the object will appear displaced towards the thinnest part of the lens, just as towards the apex of a prism; that is, in the case of a convex lens the object will be displaced away from the center of the lens. Hence, when convex lenses are so adjusted that their centers lie without the lines of vision of the two eyes, any object viewed will be displaced towards the nasal side, and consequently, in order that the image may fall upon the macula each eye must be rotated towards the nose to a greater degree than when the object is viewed without the lenses. In other words, the lenses require an increase of convergence, and the object seems nearer than it does with the unaided eye.

On the other hand, if the centers of the lenses are within the lines of vision, the lenses are comparable to prisms having their bases towards the nose, and convergence is diminished by their use.

The prismatic action of weak lenses is slight, but in lenses of high power, and especially in those required after the removal

of cataract, the disturbance arising from this action is sometimes so great as seriously to interfere with the comfort of wearing such glasses.

Prescription of Lenses.—The refractionist determines the power of the lenses which he desires his patient to wear, but if a competent optician is available, it is better to leave to him the adjustment and adaptation of these lenses in suitable frames. The refractionist must, however, be familiar with the various kinds of frames and lenses which can be supplied, in order that he may be able to assist his patient in procuring the most advantageous adjustment. He must also be able to judge as to the accuracy with which the optician has performed his work.

In an order or prescription for glasses the lens which is prescribed for each eye is indicated by the letter R (right) or L (left) as,

R + 2.50 D, sph.
L + 2.25 D, sph.

Instead of the designations *right* and *left* we may write the Latin equivalents, *O D* (*oculus dexter*), and *O S* (*oculus sinister*).

We must signify whether the glasses are for constant use or only for near work and, for the purpose of identification, we must write the patient's name and the date of the order. We may also, if we deem it advisable, specify the character of mountings to be used—whether "eye-glasses" or spectacles, frames or rimless. In filling the foregoing prescription the optician would decide whether he would supply biconvex or periscopic lenses. He would also be free to use his own judgment as to the size of the glass to be selected.

The periscopic convex lens, as commonly supplied, has a concave curvature of — 1.25 D (that is, the curvature of a plano-concave lens of 1.25 D) on the side next to the eye with a suitable convex curvature on the other side. This is the form which would be furnished by the optician in filling an order for periscopic lenses. If a greater periscopic effect is desired, the appropriate concavity should be prescribed. *Percival* and *Ostwalt* have deduced from calculation the form of curvature best adapted for extensive field of vision in various grades of lenses. Lenses may be ordered in accordance with these deductions, but for ordinary use the simpler forms suffice.

The size of the lens—or *the eye*, as it is technically called—is indicated by its number. No. 1 (37x28 *mm*) is generally used

for children, though a smaller size, No. 2, is sometimes desirable for very young children. No. 0 (39x30 *mm*) may be ordered for adolescents and small-faced adults. Nos. 00 (40x32 *mm*) and 000 (41x33 *mm*) are the sizes more commonly used for adults. For special purposes even larger sizes, 0000 and *jumbo,* may be advantageous.

Verification and Adjustment of Lenses.—We should verify the lenses which we have prescribed, and their adjustment, and for this purpose we should instruct our patient to return to us after procuring the glasses from the optician.

The method of verification has been described in a previous chapter. As to the adjustment of the lenses in suitable mountings, the glasses should be as near as possible to the eyes without touching the lashes, and the optical center of each lens should lie slightly to the inner side of the line of distant vision. If the glasses are for near use only, they should be dropped 5 *mm,* or 6 *mm,* tipped forward 15°, and the center of each glass should be carried in towards the nose 3 *mm* (*Duane*).

The following authorities have been consulted in the preparation of the foregoing chapter:

Cooper, *Practical Remarks on Near Sight, Aged Sight and Impaired Vision* (1849).

Donders, *Anomalies of Refraction and Accommodation.*

Knapp, *Die Krümmung der Hornhaut des menschlichen Auges.*

Helmholtz, *Optique Physiologique.*

Schiötz, *Untersuchungen von 969 Augen, Arch. für Augenheil.* 1885.

Landolt, *Refraction and Accommodation of the Eye.*

Baker, *Anatomy of the Eyeball,* Norris and Oliver's *System of Diseases of the Eye.*

Duane, *Refractive Errors,* Posey's *Diseases of the Eye.*

Percival, *Periscopic Lenses,* Archives of Ophthalmology, 1901.

Ostwalt, *Remarks upon Periscopic Lenses,* Ibid., 1902.

Worth, *Etiology and Treatment of Squint.*

Schirmer, *Contribution a l'Histoire de l'Astigmatisme et de l'Hypermetropie,* Annal. d'Oculistique, 1869.

CHAPTER XII

MYOPIA

Myopia (*M*) is, as previously defined, that condition in which the retina lies behind the posterior principal focus of the eye when the ciliary muscle is relaxed; or it is that condition in which the eye is too long relatively to the principal focal distance.

The word *myopia** originally indicated the practice of looking at objects through the partly closed lids, whereby the blurring of images is diminished; but as this habit is common in other conditions also, the expression is not, from a scientific point of view, without fault. *Donders* therefore proposed the word *brachymetropia*,† as corresponding with emmetropia and hypermetropia. But *myopia* is shorter and more euphonious than any of its proposed substitutes; moreover, it has the sanction of very long usage, since it dates from the time of *Aristotle*. It is therefore appropriate that its place should be retained in our ophthalmological terminology.

The expressions *near-sightedness* and *short-sightedness* are also commonly used in reference to this condition of refraction.

Curvature-Myopia

Ophthalmometric examinations have not shown any general excess of curvature, either of the cornea or lens, in myopia. Exceptionally, however, myopia is due to excessive curvature, as in keratoconus or conical cornea, in lenticonus, and in subluxation of the crystalline lens.

In keratoconus the curvature of the cornea at its apex is so great as to give rise to a high degree of myopia (Fig. 101). On the other hand, the flattening at the periphery of the cornea gives rise to hyperopia for those rays which pass through this part of the cornea. On this account when the pupil is large the vision may be better with a convex lens which corrects the peripheral rays than with a concave lens which corrects the central rays.

* From μύειν to shut, to blink, and ὤψ, sight, eye.
† From βραχὺ μέτρον, short measure, and ὤψ, sight, eye.

Lenticonus is a very rare condition. Myopia from excessive curvature of the lens is more likely to be the result of subluxation, the lens being relieved from traction of the ciliary ligament, while it remains in the pupillary area.

FIG. 101
Keratoconus

A few cases have been recorded in which there has been a sudden occurrence of hyperopia in diabetes, the probable explanation of which was given in the last chapter; more frequently, however, it has been observed in this disease that eyes which were previously emmetropic or hyperopic have become ***myopic.*** It is probable that this condition results from a curvature change, and that it is due to swelling of the crystalline lens.

Index Myopia

The only condition which, as far as we know, may give rise to index-myopia is an increase in the refractive index of the lens, such as sometimes occurs in old age, especially in the early stage of senile cataract. This increase of index may be due to an increase of density of the nucleus without a corresponding increase of density in the cortical part of the lens, or to an increase of nuclear curvature resulting from the swelling of the degenerating fibers. Since glasses which have previously been worn for the correction of presbyopia may no longer be required, the individual rejoices in the so-called *second sight*—at the expense, however, of distant vision, which becomes defective from the myopic state of refraction. This condition is usually temporary, being succeeded by declining vision as the result of opaqueness of the lens.

Axial Myopia

Myopia is ordinarily due to excessive length of the antero-posterior diameter of the eye. Excessive length as a factor in the etiology of myopia was dwelt upon by *Beer* (1792),

but it was through the demonstrations and publications of *Arlt* (1854) that the relation between axial elongation and myopia became generally understood.

The following table, constructed in accordance with the method previously described (p. 80), indicates the theoretical length of axis in various grades of myopia, as measured by the correcting lens placed at the anterior focus of the eye.

Myopia	Length of Axis	Excess
0 D (Emmetropia).........	23.2 *mm.*	
1 D........................	23.5 "	0.3 *mm*
3 D........................	24.2 "	1.0 "
5 D........................	24.9 "	1.7 "
7 D........................	25.5 "	2.3 "
9 D........................	26.2 "	3.0 "
11 D........................	26.9 "	3.7 "
13 D........................	27.5 "	4.3 "
15 D........................	28.2 "	5.0 "
17 D........................	28.9 "	5.7 "
19 D........................	29.5 "	6.3 "
21 D........................	30.2 "	7.0 "
23 D........................	30.9 "	7.7 "
25 D........................	31.5 "	8.3 "
30 D........................	33.2 "	10.0 "

We see from this table that the axial length in myopia of 3 D is 24.2 *mm.* If 1 *mm* is allowed for the thickness of the choroid and sclera, the antero-posterior diameter of the eye in this degree of myopia is 25.2 *mm.* But an axial length of 25 *mm* is not incompatible with emmetropia. Hence, in low degrees of myopia the size and shape of the eyeball differ imperceptibly, or at most but slightly, from the normal condition. In high myopia, on the other hand, and especially in that exceeding 10 D, the elongation is so great as to effect a pronounced change in the form of the eye.

As hyperopia is regarded as an imperfectly developed condition, so it might seem that the myopic eye has undergone excessive development. Since hyperopia is the normal type in the lower animals and in savages, there can be no doubt that the work to which the eyes are subjected by the requirements of civilization promotes an increased growth of these organs. Furthermore, it would be unreasonable to suppose that in this process, which occurs in conformity to the law of adaptation to use, a development which frequently stops short of emmetropia should never exceed this limit. It must be admitted, therefore, that low myopia *may* be due to physiological overgrowth of the eye. Yet in the

vast majority of cases the excessive length arises, not from overgrowth, but from stretching or distention of the ocular coats. When the myopia does not exceed a moderate degree, the stretching is so slight that anatomical examination frequently affords no positive evidence of its existence; but the fact that it is a process of stretching and not of growth is revealed by the clinical progress of axial myopia, by the increase under the strain of near work, under unhygienic conditions, and by the arrest of the process when these factors are removed.

Theories as to the Origin of Axial Myopia

While it is well established that the prolonged use of the eyes in near work is conducive to the formation of myopia, the means by which the enlargement of the eye is effected has given rise to much discussion. The various hypotheses which have been offered in explanation of the occurrence of axial elongation are divisible into two general classes. The first class embraces those hypotheses which attribute the deleterious effect of near work to the prolonged exercise of accommodation, while in the hypotheses of the second class convergence is regarded as the causal factor.

Coccius and Hjort were led to believe from their experiments that the intra-ocular pressure was increased during accommodation, and this supposition gave rise to the opinion, widely accepted, that distention of the sclera was due to the long continuance of this abnormal pressure. This hypothesis lacks confirmation, since it has never been proved that intra-ocular pressure is actually increased by accommodative action. On the other hand, experiments made by *Hess and Heine* indicate that accommodation does not cause any increase of pressure.

According to another theory, accommodation is injurious, not so much from increase of pressure, as from the traction which is exerted upon the choroid with consequent inflammatory changes followed by atrophy and thinning of the choroid and sclera. This hypothesis has as its basis the experiments of *Hensen and Voelckers,* who demonstrated a forward movement of the choroid during contraction of the ciliary muscle. There is, however, no valid reason for the assumption that this physiological movement gives rise to inflammation. Furthermore, the experiments of *Hess and Heine* show that it is only the anterior portion of the choroid

which participates in this movement, while the posterior portion alone is concerned in the development of myopia.

Those who hold accommodation responsible for the production of myopia, assign much importance to ***spasm of the ciliary muscle.*** But this is present in many young persons who never become myopic, nor is it more common in myopic than in other eyes.

A potent argument against the accommodation theory lies in the fact that there is no general tendency to increase of refraction (diminution of the hyperopia) in those eyes upon which the greatest accommodative tax is thrown, that is, in the higher grades of hyperopia.

The influence of convergence upon the form of the eyeball is doubtless of greater import than that of accommodation. When the internal recti are strongly contracted, the external recti bind closely about the outer halves of the eyeballs, and at the same time the two oblique muscles increase their traction in order to prevent the globes from sinking backward into the orbits. The pressure upon the eyes is thereby increased, ***and a direct traction (stretching) is made upon the posterior polar region of the sclera by the oblique muscles.***

Arlt advanced the theory that convergence was harmful also from compression of the posterior ciliary vessels by the external recti and inferior oblique muscles with resultant venous stasis and choroidal inflammation. *Fuchs* also claims, in corroboration of this theory, that the position of one of the venæ vorticosæ is such that it must suffer compression by the inferior oblique in convergence.

The influences which have been so far considered are such as are common to all who are engaged in exacting near work (*eye workers*); but since only a certain proportion (about 25 per cent in this country and about 50 per cent in Germany) of eye workers become myopic, it is necessary to assume the existence of *predisposing causes* in those eyes which become subject to elongation.

First, there arises the question as to the ***influence of the form of the skull*** upon the length of the eye. The largeness of the eyes and the great interpupillary distance which exists in highly-developed crania, render convergence more difficult of accomplishment than in small eyes and in those having a less interpupillary dis-

tance; hence, the large, broad type of skull is considered as a predisposing element in the formation of myopia.

Stilling believes that a low index of the orbits is a most important predisposing cause of myopia, since greater pressure is exerted upon the eyes by the oblique muscles when the orbit is low than when there is a greater interspace between the eyes and the orbits.

Insufficient length of the optic nerve has also been assigned as a possible cause of myopia (*Weiss*). Those who have advocated this hypothesis believe that in certain cases the length of the optic nerve is not great enough to permit free movement of the eyeballs, as for the easy performance of convergence; but this assumption is apparently irreconcilable with the well-known fact that a much greater degree of adduction is always possible than can be manifested in convergence.

The small or negative angle alpha, which, as shown by *Donders,* is common in myopia, has also been regarded as a factor in the production of this condition, since a greater convergence of the optic axes is required in such eyes than when the angle alpha is large.

In addition to these theoretical factors, there is to be considered the concurrence—as supported by abundant clinical evidence—of *visual defects* in myopia. Astigmia, opacity of the media, imperfect development or atrophy of the retina, or other defect which reduces the visual acuity may act as a predisposing cause of myopia, since persons who have such defects must hold objects abnormally near the eyes in order to increase the size of the images as an offset to their indistinctness.

On the other hand, the relation between the visual defect and the myopia may not be causal; both may be manifestations of imperfect development of the eye. This is, doubtless, the most potent predisposing element in the etiology of myopia, namely, *subnormal resisting power of the sclera* at the posterior pole of the eye.

Posterior Staphyloma

So great is the elongation in the highest grades of myopia that the sclera is reduced to paper-like thinness, and owing to the presence of the underlying choroid the sclera assumes a bluish tint. From this fact the condition, first described by *Scarpa* in

1807, received its name.* Scarpa did not, however, connect this anomaly with axial myopia. *Arlt*, to whom, as we have seen, is due the credit of demonstrating this relationship, erroneously regarded every axially myopic eye as affected with staphyloma—a term which is correctly applied only when there is demonstrable thinning of the sclera and atrophy of the choroid at the posterior pole of the eye.

The Conus.—The whitish area, *the myopic crescent*, which is often found at the border of the optic nerve, is called the *conus*.† The conus, which is illustrated in Fig. 102, occurs usually at the temporal border of the disk.

According to the statistics of *Loring*, this crescent is present in 20.5 per cent of myopic eyes, in 3.33 per cent of emmetropes, and in 3.49 per cent of hyperopes. From these statistics the conclusion is reached that the conus bears an important relation to

FIG. 102
The Crescentic Conus

FIG. 103
The Annular Conus

the origin of myopia, but that its presence does not necessarily indicate tendency to this affection.

The so-called *annular* or *ring conus* is due to an abnormally large opening in the sclera at the entrance of the optic nerve (Fig. 103).

There are two opinions as to the nature of the conus: (1) That it is a circumscribed atrophy of the choroid, due to stretching of this membrane in axial elongation, and (2) that it is a congenital peculiarity of development.

* From σταφυλή, a bunch of grapes.

† The conus (*Jaeger*) originally denoted the irregularly cone-shaped patch of atrophy extending from the crescent in staphyloma, but this term is now commonly used in reference to the crescent or to the exaggerated scleral ring.

The former hypothesis is discredited by the regularity of outline of the conus, by its occurrence in emmetropic and hyperopic eyes, and by anatomical examinations, which have shown that in emmetropia and hyperopia and also in mild myopia the sclera and choroid are perfectly normal beyond the limits of the conus.

The second hypothesis—that the conus is due to congenital anomaly of development (absence of the anterior layers of the choroid, pigment, and retina)—has been strenuously urged by *Schnabel,* who claims that his opinion is confirmed by microscopic examinations.

Since it is a matter of clinical observation that a conus sometimes appears in an eye which has previously seemed free from this anomaly, Schnabel assumes that the conus was previously present, but that, being very small, it was not noticeable until, with an increase in the size of the eye, there occurred a corresponding increase in the size of the conus.

Two Theories as to the Origin of Posterior Staphyloma.—In accordance with these two theories as to the nature of the conus, there are two corresponding theories as to the origin of posterior staphyloma. Those who believe that the conus is ascribable to atrophy of the choroid, believe also that the strain of near work may give rise to posterior staphyloma in an eye of perfectly normal development. On the other hand, those who see in the conus evidence of anomalous development believe that in addition to this defect there is in all staphylomatous eyes deficient development of the sclera at the posterior polar region.

While the conus is found in only about 20 per cent of myopic eyes, it exists in practically all in which there is staphyloma; hence, if we accept this theory, the presence of the conus must be regarded as evidence, but not positive evidence, of congenital deficiency in resisting power of the sclera

Whether we do or do not accept Schnabel's views as to the nature of the conus, clinical evidence is largely in favor of the theory that staphyloma occurs only in eyes of congenitally defective development. None of the influences which have been detailed as giving rise to myopia suffices to explain the occurrence of staphyloma in an eye of normal development. In such an eye the thickest and most resistant portion of the sclera is in the region of the optic nerve and posterior pole, and any increase of intraocular pressure which might result from near work would not be

limited in its manifestation to this part of the eyeball. This is exemplified in glaucoma in young subjects, in whom distention of the sclera is general, but is most marked in the region anterior to the insertions of the recti muscles, where the sclera is thinnest.

The theory of traction by the optic nerve is equally incapable of accounting for the ectasia at the posterior pole, for the maximum effect of such traction would occur in the neighborhood of the disk, not at the pole.

In order to explain by this or other theory the occurrence of the circumscribed polar ectasia, we must assume the coexistence either of choroidal inflammation extending to the sclera or of defective development. Against the former assumption are the clinical facts that choroiditis does not in general extend to the sclera, and that choroidal complications occur, not before, but after the scleral ectasia.

But the most potent reason for believing that the insufficient resisting power of the sclera is congenital lies in the fact that the scleral ectasia almost always commences at an early age, before the eyes have been subjected to the injurious influences of near work. The eyes of newborn children are, as a rule, hyperopic; but it is beyond dispute that high myopia with staphyloma occurs at an early age. Among other cases which have been reported may be cited the following: myopia of 11 D at the age of eighteen months (*Eales*), 10 D at the age of six months (*Cant*), 17 D at the age of four years (*Wray*). These are extreme cases, but the occurrence of myopia varying from 4 D to 8 D in children under six years of age is by no means rare among the poorly-developed lower classes. These are the cases which, unless checked by suitable treatment, always terminate in staphyloma with high myopia.

Anatomical and Ophthalmoscopic Characteristics.—The thinning of the sclera in posterior staphyloma is confined mainly to the segment which extends medially slightly beyond the edge of the optic nerve, and laterally to the attachment of the inferior oblique muscle. The region of the posterior pole or of the macula consequently lies near the center of the staphylomatous area, and the greatest protrusion occurs in this position. This is illustrated in Fig. 104, in which the optic nerve lies on the side of the protrusion; but sometimes the ectasia extends more medially, and then the optic nerve lies, not as illustrated, but at the bottom of the protrusion.

In connection with the oblique position of the papilla there occur also peculiar changes in the appearances of the optic nerve in its passage through the sclera and choroid. Opposite to the crescent the choroid and retina seem to be drawn over the medial border of the nerve, as if the whole posterior portion of these membranes had shifted its position. This is the so-called supertraction of the choroid of *Nagel and Weiss*. Furthermore, the entire head of the optic nerve is distorted, as if drawn over by

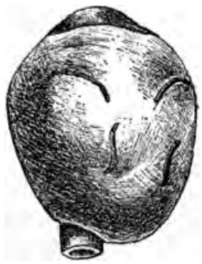

FIG. 104

The right eye of a woman fifty-six years of age, with a large posterior staphyloma; myopia, about 25 D; length of axis, 30 millimeters. (*Schnabel.*)

distention of the sclera towards the staphyloma. This distortion is accompanied also by an abnormal size of the intervaginal space, as if the nerve had been drawn away from its normal attachment with consequent separation of the nerve sheaths (Fig. 105).

Ophthalmoscopically the oblique position of the papilla is a marked characteristic in staphyloma. It gives the disk an apparently oval form, which is accentuated when the retina extends over the medial border of the nerve.

Two Types of Axial Myopia

In accordance with the foregoing facts, we conclude that there are two types of axial myopia. The first type embraces those cases which result mainly from the strain of near work during school-life, or from other exacting eye work. The refraction is, in this type, hyperopic in early childhood, and would probably remain so—or at least not pass the limit of emmetropia—during life if near work were excluded; but the irritation induced by the educational process leads to an increase in size of the eye, and myopia results. This most often occurs between the ages of ten and twenty years. The progress of the myopia may be arrest-

ed in childhood or it may continue until the body has attained its full growth. After this the sclera is more resistant, and the myopia remains stationary. It rarely, if ever, reaches a high degree. We may assign 6 D as the limit, beyond which it does not often pass.

In myopia of this type the sclera does not undergo any appreciable thinning, and neither ophthalmoscòpic nor anatomical examination reveals any defects except the conus, which may or may not be present.

Although distant vision without glasses may be very defective, yet because this type of myopia is not accompanied by atrophic and other pathological changes, all such cases are classified as belonging to the *mild* type of myopia. Since such myopia is acquired during school-life, it has also been called *acquired* or *school* myopia.

The second type of axial myopia embraces those cases which are dependent upon posterior polar ectasia. Every case of axial myopia which exceeds 10 D may be assigned to this class (*Schnabel*), but even a moderate myopia (3 D or 4 D) occurring at an early age must be regarded as indicative of defective scleral development, which may subsequently give rise to staphyloma with great increase of the myopia.

The stretching of the choroid and retina in staphyloma is first manifested by an increase in size of the crescent, and subsequently by atrophic changes in these membranes. The process commences at the outer border of the crescent; the latter loses its regular contour and becomes merged in the larger, irregularly shaped, whitish patch. The atrophic area continues to increase in size and it sometimes surrounds the entire disk, as in Fig. 105 (*annular staphyloma*). Other atrophic patches appear, in the worst cases, at or near the macular region, and these are very disastrous to vision. Moreover, there is interference with the nutrition of the eye, so that other grave dangers threaten destruction of the small amount of vision which remains. Where the atrophic areas are surrounded by accumulations of pigment, the changes are not recent. An ill-defined yellowish patch signifies that the atrophy is still progressing. Not infrequently the atrophy progresses by intermittent stages, which are distinguished by separating lines, more or less defined, and marked at times by accumulation of pigment.

Since in this class the myopia tends to increase, even after adult life is reached, and since even when the myopia itself has become stationary, atrophy, hemorrhage, opacities, and retinal detachment still threaten the eye, the name ***progressive*** or ***malignant*** myopia is appropriate.

Of those cases of axial myopia which are more than 6 D and less than 10 D, a minority may be exaggerated types of ac-

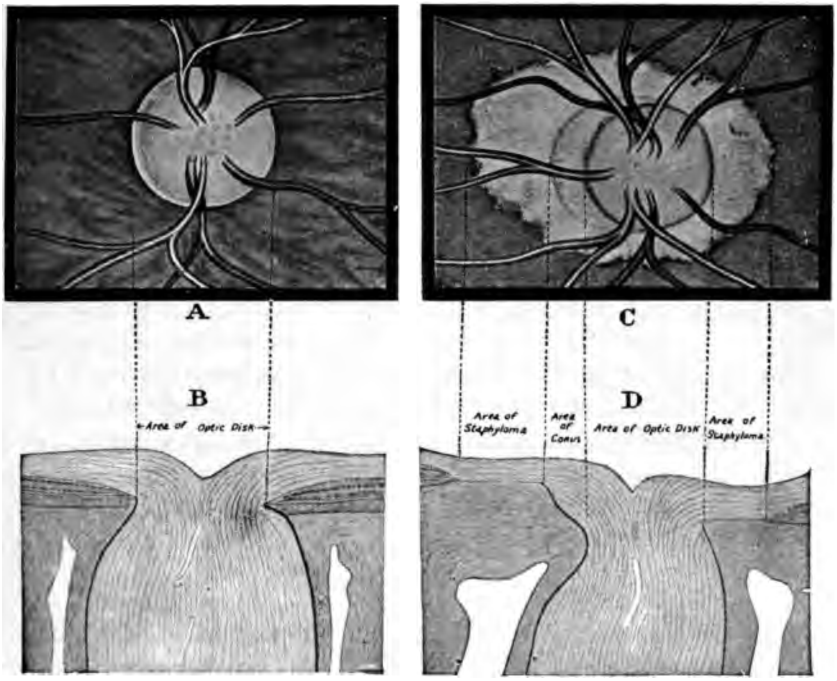

FIG. 105

Normal Eye
A; Ophthalmoscopic view.
B; Diagrammatic section.

Posterior Staphyloma
C; Ophthalmoscopic view.
D; Diagrammatic section.

Optic Nerve Entrance (*Herrnheiser*).

quired myopia; but for the most part they must be regarded as favorable cases of staphyloma. In fact, it is probable that in all such cases a deficiency in the development of the sclera has existed, and that at least in the greater proportion the elongation commenced prior to the age of near work. In those cases which do not become decidedly staphylomatous, the strength of the sclera is not greatly reduced, so that the elongation is arrested before the development of very high myopia

Statistics of Myopia

Many statistics have been published in regard to myopia. In those in which a large number of eyes was examined, the results are fairly uniform. These statistics relate mainly to the proportion of myopes at different ages, in different races, and in different occupations.

Of statistics which refer to *the proportion of myopes at different ages and in different races, Loring* attaches especial importance to the results of four observers: *Erismann*, of St. Petersburg; *Conrad*, of Königsberg, and *Derby and Loring*, of New York. A large number of eyes was examined by each of these observers, and the conditions were similar in all cases. The examinations were all made on school-pupils between the ages of six and twenty-one years.

According to *Erismann's* statistics (4358 pupils), 10 per cent were myopic in the lowest classes, the proportion increasing to 42 per cent in the highest; *Conrad's* statistics (3036 pupils) showed 11 per cent of myopia in the lowest classes and 62 per cent in the highest; *Derby and Loring's* (2265 pupils) showed 3.5 per cent in the lowest and about 27 per cent in the highest classes.

Many other investigators have published statistics bearing on this subject, but those here given are sufficient to convince us that myopia is very frequently acquired during school-life, and that Americans are much less subject to this affection than Europeans.

Statistics have also been published showing *the change in refraction in the same individuals with increase of age*. Among these may be mentioned those of *Erismann* (350 eyes re-examined after the lapse of six years), of *Reich* (85 pupils, after six years), and of *Cohn* (138 pupils, after one and one-half years). These statistics all show that there is a general tendency to increase of refraction (diminution of hyperopia or increase of myopia) prior to adult life, and that this tendency is most marked in those who are already myopic. In no case do they show that an eye previously recorded as hyperopic or emmetropic has attained a degree of myopia exceeding 6 D.

Of the statistics relating to the *degree of myopia* among a large number of myopes, those of *Schweizer* must be mentioned as being particularly useful. Among 5039 myopic eyes the myo-

pia did not exceed 6 D in 4029 of these; in 475 eyes it was between 7 D and 10 D, and in 535 eyes it was more than 10 D.

Tscherning has published very instructive data showing *the proportion and grade of myopia among different classes* of persons. He found that of 2336 eye-workers, 18 per cent were myopic; of 5187 laborers, 4 per cent were myopic. But of the myopic eye-workers, only 3 per cent had myopia exceeding 9 D, while of the myopic laborers 18 per cent had myopia exceeding 9 D. These figures indicate very clearly that while near work has a decided influence in the etiology of mild and moderate degrees of myopia, it is not a predominant factor in the production of posterior staphyloma.

Statistics have also been published with a view to showing, by comparison with the older statistics, *the beneficial effect which hygienic care of the eyes of the young has exerted upon the proportion of myopes. Risley* especially has made extensive investigations of this subject. His data, as well as those of others, indicate that a perceptible improvement follows the introduction of school hygiene.

Lastly, statistics have been published setting forth *the influence of heredity* in the etiology of myopia. These statistics show not only that some races are more liable than others to myopia, but also that the members of certain families possess in a special degree the characteristics which lead to the formation of this anomaly.

Symptoms of Myopia

Myopia of every grade is characterized by one predominant symptom:—the inability to see distant objects clearly. Even in myopia of .5 D vision at six meters or more is perceptibly below the normal. But as the power of analyzing objects varies, so with the same amount of error the vision will vary according to the intelligence of the individual, the familiarity with the object under examination, and the size of the pupil of the eye.

The symptoms of eye-strain (asthenopia and congestion of the retina) which were described as occurring in hyperopia occur also in myopia. These symptoms are regarded by some ophthalmologists as indicating that the ocular membranes are undergoing a process of stretching. Whether or not this is the case. such symptoms can not be said to play an important part in the etiology

of staphyloma, since they frequently occur in eyes in which the elongation never passes the limit of emmetropia.

Muscular asthenopia, due to disturbance in the relation between accommodation and convergence, is a not uncommon symptom in myopia. Owing to the weak accommodative impulse required, the convergence-center is insufficiently stimulated, and insufficiency of convergence results.

Insufficiency of convergence occurring in myopia may be due not only to the disturbed relation between accommodation and convergence, but also to some anatomical peculiarity requiring unusual effort to produce convergence, such as abnormally great interpupillary distance, elongated eyeball, or unfavorable insertions of the internal recti muscles.

Divergent Strabismus in Myopia.—When the myopia exceeds 4 D, so that the far-point is less than one-fourth of a meter from the eye, binocular near work is almost always burdensome, because of the great tax on the convergence. On this account myopes of this class generally abandon binocular vision (if they do not wear correcting lenses), using only one eye in near work, while the other eye turns relatively outward to a greater or less degree. The parallel direction may be maintained in distant vision; but frequently binocular distant vision is abandoned, and the unused eye becomes permanently divergent, the latent insufficiency passing into manifest strabismus. Hence, *divergent strabismus* is a not infrequent symptom of myopia, and especially of that exceeding 4 D.

Symptoms Arising from Disturbed Nutrition in Staphyloma.—In the high grades of myopia the far-point lies only a few centimeters from the eye, and consequently, reading matter or small objects to be deciphered must be held just beyond the tip of the nose; but this is by no means the gravest symptom of staphyloma. Those symptoms which arise from defective nutrition of the eye are such as to give to the myopia a position of secondary importance. Floating opacities in the vitreous body, high astigmia from partial dislocation of the lens, polyopia from commencing cataractous degeneration, fixed scotomata from retinal atrophy or hemorrhage, metamorphopsia from serous effusion beneath the retina, and total blindness from retinal detachment are among the complications that are liable to occur in myopia with posterior staphyloma.

Diagnosis of Myopia

Externally there is nothing markedly characteristic of mild myopia; but the elongation in staphylomatous eyes is apparent in the facial expression. Such eyes are usually prominent and their large size is especially noticeable when they are turned sharply to one side. In addition, there is generally found an abnormal depth of the anterior chamber in the highest grades of myopia. These appearances are, however, mere incidentals, since the myopia and its degree may be readily determined by application of the tests which were enunciated in Chapter X.

The order of applying these tests which was suggested for the measurement of hyperopia may be followed also in myopia, namely, *ophthalmometry* (for the determination of coexisting astigmia), *skiascopy, ophthalmoscopy,* and the *subjective examination* with trial lenses.

The rule which was advised for the employment of a cycloplegic in hyperopia is applicable also in myopia. While perhaps in a greater proportion of cases the true refractive condition may be ascertained without cycloplegia in myopia than in hyperopia, yet there is no certainty as to the correctness of the result in young persons unless the accommodation has been paralyzed.

The ophthalmoscopic examination assumes a relatively greater importance in myopia than in hyperopia, since by it we are informed as to the condition of the interior of the eye—whether the myopic crescent, choroidal atrophy, macular disease, opacity of the vitreous body, or other accompaniment of staphyloma is present.

Differentiation of Mild and Malignant Myopia.—There are three points to be especially considered in making the distinction between these two kinds of axial myopia:

(1.) *The Age at which the Myopia Develops.*—Myopia occurring before the age of near work always indicates defective scleral development, which, unless promptly arrested, will probably terminate in staphyloma. On the other hand, myopia which is evolved from a condition of hyperopia during school-life, is indicative of the mild form and will not lead to destructive processes in the eye.

(2.) *The Degree of Myopia.*—Myopia which is less than 6 D in an adult may be regarded as having been acquired during

school-life and, therefore, as belonging to the mild form; or, exceptionally, it may denote an infantile myopia in which the progress of ectasia has been arrested, and in which further advance is not to be expected. Myopia which is between 6 D and 10 D must be regarded as probably due, in adults, to arrested ectasia; in youth an advancing process must be assumed. Myopia exceeding 10 D always indicates staphyloma.

(3.) *The Ophthalmoscopic Appearances.*—The presence of the conus is evidence of staphyloma only in that while frequently absent in mild myopia it is always found in staphyloma. Positive proof of staphyloma is afforded by the existence of choroidal atrophy extending beyond the border of the crescent with or without atrophy in the macular region.

Diagnosis of Curvature-Myopia and Index-Myopia.—In the small minority of cases in which high myopia is due to conical cornea, the characteristics are altogether different from those in axial myopia. The symptoms of posterior staphyloma are absent, while the excessive curvature of the central portion of the cornea is revealed by keratometry, by skiascopy, and by the unaided eye in advanced cases.

The myopia which occurs in old age from swelling or increase of density of the nucleus of the lens is also readily differentiated from axial myopia by the period of life at which it develops, by the abnormally intense nuclear reflex, and by the detection of lenticular opacities.

Treatment of Myopia

Since it is well established that prolonged near work tends to favor the myopic state of refraction, and since it would be a grave misfortune if, with the advance of civilization, myopia should become the ordinary condition of the human eye, we must do all that is in our power to combat this tendency by hygienic and artificial means. Whatever acts favorably in the individual exerts also a beneficial influence upon the resisting power of the eyes of future generations.

Prophylactic Measures.—Young children should not be permitted to indulge in exacting near work, since it is at this period that the sclera is most distensible. They should not commence school before the completion of the seventh year of age; and at the beginning of school-life and at least once a year there-

after the vision should be tested in order that those in whom it is found defective may receive appropriate treatment.

The correction of astigmia is especially important, since the defect of vision caused by it necessitates an abnormal approximation of objects, with excessive strain on the accommodation and convergence.

When the vision is markedly defective and is incapable of improvement, the child should not be permitted to pursue the full course of study required of healthy children.

Since anything that interferes with the bodily nutrition must exert an unfavorable influence upon the strength of the sclera, and since posterior staphyloma is most liable to occur in children of defective constitution, it is essential that school hours should be broken by suitable out-of-door exercise, and that other matters of general hygiene should receive proper attention.

Of no less importance are the arrangements of the schoolrooms as to light and ventilation, and the adaptation of the desk to the pupil (for the avoidance of the stooping posture with the consequent congestion of the head and eyes), and the quality of the paper and print used in the text-books. Much thought has been given this subject of school hygiene of late years, and great improvements have been effected.

The attention given these matters should extend also to office rooms and factories, in which the eyes of the employees are taxed to the utmost during a period of eight or ten hours each day. In those occupations which necessitate the prolonged examination of small objects, a magnifying glass, such as is used by watchmakers, should be employed as far as possible. By this means both accommodation and convergence are relieved of the strain to which they would otherwise be exposed.

Use of Lenses in Myopia.—While all authorities are agreed as to the beneficial effect of hygienic measures, the influence of correcting lenses upon existing myopia is a question about which there has been some difference of opinion. Those who believe the myopia to be the result of over-exercise of accommodation condemn the use of concave lenses in near work. Those, on the other hand (including the large majority of ophthalmologists of the present day), who believe that convergence, not accommodation, is the main factor in the production of myopia, deny any evil effect of concave lenses. Furthermore, it is claimed

that by restoring the eye to its normal condition of emmetropia, a beneficial influence is exerted upon the progress of the myopia. In support of this view is the clinical fact that with the relief from asthenopia effected by the constant use of glasses, the progress of the myopia is frequently checked.

As in hyperopia, so in myopia, no general rule can be given for the prescription of lenses; but there is this difference: in hyperopia correction is not essential as long as the condition gives rise to no disturbance, and the younger the child the less commonly is correction required (except in strabismus); whereas myopia occurring in childhood requires correction in every instance and at the earliest age compatible with the wearing of spectacles.

In childhood and youth the entire myopia, or all but a small fraction, should be corrected and the glasses should be ordered for constant wear. But in myopes who have passed early adult life without correction of their refractive error, the ciliary muscle is untrained and imperfectly developed, and total correction of the myopia will not be tolerated for near work. The course to be pursued in these cases varies with the degree of myopia and with the attendant circumstances. We may make the following classification:

(1) When the myopia is not more than 3.5 D or 4 D, and especially if the presbyopic age has been reached, lenses may be used for distance, while near work is performed without the myopic correction.

(2) When the myopia exceeds 4 D, vision being binocular, concave lenses are imperative in near work, since without lenses the strain on the convergence is too great to be comfortably and safely endured. The far-point must be so removed by lenses that no more than 3.5 *ma* or 4 *ma* of convergence will be required.

(3) When vision is monocular concave lenses are not usually acceptable in near work, since larger images are obtained without the lenses, and without any exercise of accommodation or of convergence. In this class, to which belong the majority of those having myopia of high degree (which has not been corrected in early life), concave lenses are in many cases rejected also for distant vision, or are accepted only for momentary use.

The treatment of muscular disturbances directly dependent

upon myopia consists in the application of the appropriate concave lenses, and the earlier the age at which relief is sought, the greater is the likelihood of a successful result. Other measures, which may be required in neglected cases, are described in Chapter XVII.

Use of Tinted Glasses.—Although tinted glasses are not advisable for permanent wear in healthy conditions of the eye tunics, such glasses are sometimes required in the diseased conditions attending high myopia.

Secondary Effects of Concave Lenses.—The secondary effects of concave lenses are opposite to those which were noted (Chapter XI) as occurring in the use of convex lenses. There are chiefly to be considered the prismatic effect, the actual minification of the retinal image, and the apparent minification due to the erroneous judgment as to the distance of the object. There is also alteration in the relation between accommodation and convergence, which may give rise to disturbance when the lenses are first worn; but more frequently this change is advantageous, since insufficiency of convergence is very common in uncorrected myopia.

Prescription of Concave Lenses.—The directions which were given for the prescription of convex lenses apply also to the ordering of concave lenses.

Concave lenses are usually supplied either in the biconcave or the periscopic form. In the latter the outer face of the lens has the curvature of a plano-convex lens of + 1.25 D, while the appropriate concavity is ground on the other surface, which is placed towards the eye. In the absence of any special instructions, the optician would be at liberty to use his discretion in the choice between these two forms. If a greater periscopic effect is desired than that which is afforded by the ordinary form of the periscopic lens, the required degree of concavity must be specified.

Operative Treatment of Axial Myopia.—Because of the disadvantages attending the use of strong concave lenses, with the consequent rejection of them by many myopes, it was many years ago proposed that the crystalline lens should be removed for the relief of such persons. It is said that this procedure was first suggested by Gottlieb Richter, of Göttengen,

about the year 1790. It was not carried into execution, however, until *Mooren,* in 1854, performed a discission operation upon an eye affected with high myopia. This case was successful, but later Mooren met with failure, and the method fell into ill repute, until in 1887 *Fukala* revived it by operating successfully in a number of cases. Other ophthalmologists followed Fukala's example and many hundreds of cases have been reported. The operation as now usually performed consists of two stages. In the first stage the lens is rendered cataractous by discission, while the second stage consists in removal of the lens through a linear incision. An interval of a few days must elapse between the two stages, the exact time being determined by the condition of the lens and the tension of the eye.

While removal of the lens is a much safer procedure at the present day than it was when Mooren first undertook it for the cure of myopia, yet, owing to the diseased condition of the eye in posterior staphyloma, the operation must always be attended with serious risks, as of hemorrhage and detachment of the retina. This method is, therefore, limited in application. It is especially indicated in those persons in whom continuance in their occupation is impossible without some greater improvement of vision than can be obtained from glasses. The operation is contraindicated in old persons. As a rule, forty years should be regarded as the age limit (*Fukala*), though older persons have been operated on successfully.

The effect of removal of the lens upon the refractive condition of the eye and upon the size of retinal images varies with the axial length (Chapter V). We have learned that if the refracting surfaces are normal in position and curvature, about 24 D of myopia will be neutralized by removal of the lens, and that the linear dimensions of the retinal image will be about one and one-half times as large as in the normal eye. In practice these figures are only approximately correct. As the degree of alteration in the refractive condition produced by lens-removal diminishes with the axial length, the degree of myopia which may furnish emmetropia in the aphakic condition varies within quite wide limits. A condition approximating emmetropia may result from removal of the lens in myopia varying from 16 D to 25 D. Because of the great individual variation, the empiric rules which have been given, as the result of averages deduced from numerous

operations, are of no practical assistance in determining the probable post-operative refractive condition.

In view of the foregoing considerations, it is apparent that operative procedure is contraindicated when vision is so low from macular degeneration that the improvement to be expected from enlargement of images (and in some cases from the removal of an imperfectly transparent and irregularly refracting lens) could afford no useful sight. The least degree of myopia in which removal of the lens is permissible is about 12 D, and usually 15 D is a more appropriate limit.

Operative Treatment of Conical Cornea.—Since only a small proportion of the extremely high myopia caused by conical cornea would be relieved by removal of the lens, such treatment would be of no material benefit in this affection. In order to ameliorate the distressing condition of the subjects of this disease (lenses being particularly unsatisfactory because of the hyperboloidal form of the cornea), cauterization of the apex of the corneal protrusion has been advocated and practised by ophthalmic surgeons. The excessive curvature is diminished by the flattening which takes place with the process of healing. A subsequent iridectomy may be required on account of the central scar-formation.

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CHAPTER XIII

ASTIGMIA

Astigmia of the eye (*As*), usually called astigmatism, has already been defined as that condition in which, because of irregularity or asymmetry of refraction, homocentric rays lose their homocentric character in passing through the ocular media.

We have learned that there are two kinds of astigmia, *regular* and *irregular,* according as the defect is due to asymmetry or irregularity of refraction. As the word astigmia (or astigmatism) is used without qualification it refers to the regular variety of this anomaly.

Astigmia was noted by *Thomas Young* (1801), who by means of his optometer discovered that he had this defect in his own eye.

Young excluded asymmetry of the cornea in his case by immersing the eye in water (by which means the corneal refraction is almost entirely neutralized), replacing the corneal refraction by the action of a convex spherical lens, and observing that the astigmia remained unchanged. Since the defect was not in the cornea, he inferred that it was due to an oblique position of the crystalline lens.

Sir George Airy, who had myopia with astigmia, first wore spectacles correcting the defect (1827), but the introduction of cylindrical lenses into common use was accomplished through the advocacy of *Donders.* Our practical knowledge of astigmia dates from the invention of the ophthalmometer by *Helmholtz,* and from its use by him, by *Donders, Knapp,* and others.

No definite name was given either by *Young* or by *Airy* to the anomaly which they discovered in their own eyes. Later *Dr. Whewell,* an eminent scholar and a friend of Airy, suggested that this defect be called *astigmatism.* This word soon came into general use, and even at the present time it is the commonly accepted term.

Attention was first called to the incorrectness of the word astigmatism by *Dixon,* who, in an article on Vision in Holmes' System of Surgery (1881) wrote:

"Astigmism would be the more correct term στιγμή (στιγμῆς) being commonly used by Greek writers to express a geometric point, while

στίγμα (στίγματος) always signifies something material, more or less visible or tangible—a puncture, mark or spot. I took the liberty of pointing this out to the late eminent scholar, Dr. Whewell, who had originally suggested the word astigmatism, and he approved of astigmism as being etymologically the better formed word."

The word *astigmism,* which Dixon suggested, is not much more desirable than the word which it was intended to replace. It would be manifestly unwise to attempt to reform our terminology solely for etymological reasons, as this would involve us in many difficulties.

Astigmia, the word which I have adopted, has a more agreeable sound, and it also has the advantage that it has to some extent come into use.

None of the foregoing words makes the distinction between asymmetrical refraction in general and such refraction as a defect of the eye. The latter condition would be properly called *astigmopia,* but this, being a somewhat cumbersome and an unfamiliar word, would probably not find ready acceptance. I have, however, made use of the word *astigmope,* as corresponding with myope and hyperope, since there is no other word which conveniently takes its place.

The physiological astigmia which results from slight imperfection is not noticeable in ordinary vision, but when one looks at a point of light, as a star, the image on the retina is not a point, as it would be if the eye were perfectly formed. Owing to irregular astigmia, the star appears as a bright center with lines of light (rays) proceeding in various directions from this center. The more free an eye is from astigmia the less marked is the ray-like appearance. But that such appearance is well-nigh universal is attested by the time-honored custom of picturing a star, not as a round body, but as sending forth streams of light in various directions.

Etiology of Corneal Astigmia

Regular corneal astigmia is due, in the vast majority of cases, to asymmetrical development of the eyeball—a defect which is usually congenital, though it is sometimes acquired after birth.

We have learned that in those eyes which may be regarded as normal the curvature of the cornea is, *as a rule,* slightly greater in the vertical than in the horizontal meridian. In assuming this form the cornea follows the form of the eyeball, which is slightly shorter in the vertical than in the horizontal diameter; and this, in turn, conforms to the shape of the orbit, which offers its least dimension in the vertical meridian. Exaggeration of this normal asymmetry gives rise to astigmia in excess of the amount which can be regarded as physiological.

Relation of Astigmia to Cranial Development.—But the foregoing explanation serves only for such asymmetry

as presents the greatest curvature in the vertical meridian. Occasionally the cornea presents its least curvature in the vertical meridian, the greatest curvature being in the horizontal meridian, or the meridians of greatest and least curvature may be neither vertical nor horizontal (*oblique*). An attempt has been made to prove that all such astigmia (and, in fact, that all congenital astigmia) occurs in connection with and results from faulty or asymmetrical development of the cranium. While this connection cannot be universally verified, we frequently observe that a high degree of astigmia coexists with defective cranial development.

Change in the Form of the Cornea.—The cornea attains its full growth at an early age, about the third year. In accordance with this fact, keratometric observations which have been repeated upon the same persons after the lapse of a number of years show that very little change takes place in the form of the cornea after it has attained its growth. Exceptionally, however, measurements have revealed a decided asymmetry in a cornea which had previously been found free from this defect. Such change of form may be ascribed to pressure upon the cornea by the eyelids, to tenotomy or advancement of an extra-ocular muscle, or to asymmetrical increase in the size of the eyeball.

But the only common cause of a decided change in the form of the cornea is the interposition of scar-tissue, either as the result of disease (suppuration) or of traumatism (corneal section). In the former case the astigmia is, for the most part, irregular; but with this a certain amount of regular astigmia, capable of correction, may also occur. A high degree of regular astigmia is the rule after corneal section, as in cataract-extraction. The alteration in curvature is greatest immediately after the operation, and gradually diminishes, sometimes vanishing entirely. After the lapse of six months no further change is to be expected.

Etiology of Lenticular Astigmia

We have learned that the angle alpha, which measures the tilting of the lens with reference to the optic axis, usually extends downward and outward, varying in the horizontal meridian between four and seven degrees, and in the vertical meridian between two and three degrees; we have also learned that

this tilting produces only a slight degree of astigmia, and that the principal factor in the etiology of astigmia of the crystalline lens is asymmetry of its posterior surface.

A marked increase of lenticular astigmia occurring after birth is usually attributed to a partial dislocation of the lens, as the result of traumatism or disease.

Dynamic Astigmia.—The hypothesis of dynamic compensatory astigmia was first announced by *Dobrowolsky* in 1868. In this hypothesis it is assumed that by a partial or asymmetrical contraction of the ciliary muscle a certain amount of astigmia can be produced for the correction of an opposite corneal astigmia.

As the result of clinical and experimental observations many other authorities were led to accept the conclusions of Dobrowolsky; and with the introduction into general use of keratometry compensatory astigmia was assigned by *Javal* as a potent factor in causing the discrepancy between the keratometric record and the subjective astigmia.

Supported by these authorities, the hypothesis has been widely accepted. The amount of compensatory action which has been assigned to the ciliary muscle varies, according to different authorities between 1 D and 3 D.

There must be considered, as of the utmost importance in reaching a correct conclusion in the study of this subject, the ability of the individual to decipher diffusion-images, the inability to discriminate between perfectly sharp images and those formed with slight diffusion, the stenopæic effect of partially closing the lids, and the variation in the size of the pupil, especially in comparing the tests of vision with cycloplegia and without it.

Having eliminated these sources of error, *Hess* proceeded to determine by experiment whether or not partial accommodation is possible. His device consisted essentially of two cotton threads stretched at right angles to each other. The stands supporting the threads were movable along a graduated rod. The astigmia (natural or artificial) of the examinee being known, the vertical thread, for instance, was placed at the near-point of the horizonal meridian of the eye, while the horizontal thread was placed at the near-point of the vertical meridian. By moving one of the threads, the power of the eye to accommodate in one meridian could be ascertained. Having examined in this way twenty-three individuals, Hess found that in no case could

the highest possible partial contraction exceed .37 D, and it was often less than .1 D, that is, *not that this amount of partial accommodation actually existed, but that it could not be excluded by the test.*

Although it is possible, *even probable,* that contraction of the ciliary muscle may in certain instances be more effective in one meridian than in another, yet the belief that we are able to control this action for the correction of astigmia, is in my opinion wholly untenable, for it requires the highly improbable assumption of the existence of a separate nerve nucleus for each principal meridian.

Degree of Astigmia

The degree of regular astigmia varies from an inappreciable amount to 15 D or more. In a few instances only has an amount reaching the latter degree (15 D) of congenital astigmia been recorded. A very high degree of astigmia has occasionally been measured with the keratometer shortly after the healing of corneal section, only a minor portion of which, however, is permanent. With the exception of such, an amount exceeding 6 D is of infrequent occurrence.

Donders and others of the older ophthalmologists regarded astigmia of less than 1 D as physiological and as not requiring correction; but at the present day .25 D, or even .12 D is considered sufficient to call for correction.

Classifications of Astigmia

Classification with Reference to the Position of the Principal Meridians.—Since the meridian of greatest curvature of the eye is, *as a rule,* vertical or nearly so, the astigmia which results from this kind of asymmetry is said to be *with the rule,* or *direct.*

When, as sometimes is the case, the meridian of greatest curvature is horizontal, the astigmia is said to be *against the rule,* or *indirect,* or *inverse.*

Corneal astigmia is usually direct, the meridian of greatest curvature being vertical, or nearly so. Indirect asymmetry occurs in young persons only in about 1.3 per cent of eyes (*Nordenson*). According to *Pfalz* the cornea undergoes a gradual change from

youth to old age, so that in the latter period of life indirect corneal astigmia is comparatively frequent.

The astigmia which results from the ordinary corneal section (upward) for cataract-extraction is indirect, since the section diminishes the vertical curvature without materially altering the horizontal curvature.

The astigmia which results from the oblique position of the crystalline lens is *indirect,* as is usually that which results from asymmetry of curvature of the lens.*

Oblique astigmia is that condition in which the principal meridians are not vertical and horizontal (or nearly so), but make angles of forty-five degrees (approximately) with the vertical and horizontal lines. The distinguishing limit between direct or indirect astigmia and oblique astigmia, as thus defined, is arbitrary; but it is customary to regard astigmia as oblique when the principal meridians are more than twenty degrees from the vertical and horizontal lines.

Classification with Reference to the Relative Directions of the Principal Meridians in the Two Eyes.—In the majority of astigmopes the defect is *symmetrical; that is, the meridians* of greatest and least curvature correspond in the two eyes.

If the meridian of greatest curvature is vertical in one eye, the probability is that the meridian of greatest curvature of the other eye is also vertical. So also, if the upper extremity of the meridian of greatest curvature lies on the temporal side of the vertical meridian in the right eye, the probability is that the meridian of greatest curvature of the left eye lies on the temporal side of the vertical meridian, and that the angle of inclination to the vertical meridian is the same, or nearly so, in the two eyes.

We must observe, however, that with the angular notation in common use in this country the degree markings are not the same in the two eyes. If the meridian of greatest curvature is denoted by 45° in the right eye, the corresponding marking for the left eye is 135° (90+45).

When the meridian of greatest curvature (*not being vertical or horizontal*) is marked by the same angle (Fig. 86) in

*The astigmia which results from asymmetry of the posterior surface seems to be invariably indirect.

the two eyes—that is, when the meridian of greatest curvature is inclined towards the temple in one eye and towards the nose (to an equal degree) in the other—the astigmia is said to be *asymmetrical* but *homologous.*

When the meridians of greatest curvature in the two eyes are neither symmetrical nor homologous, as, for instance, when one eye presents the greatest curvature in the vertical meridian and the other in the horizontal meridian, the astigmia is *asymmetrical* and *heterologous.* This kind of astigmia is of comparatively infrequent occurrence.

Classification with Reference to the Relation between the Position of the Retina and that of the Focal Lines.— *Simple hyperopic astigmia* (*H As* or *Ah*) is that condition in which, the accommodation being relaxed, one focal line falls upon the retina while the other lies behind it; or, it is that condition in which the eye is emmetropic in one principal meridian and hyperopic in the other.

Compound hyperopic astigmia (*H As Co.* or *H + Ah*) is that condition in which both focal lines lie behind the retina; the eye is hyperopic in both principal meridians, but more so in one than in the other.

Simple myopic astigmia (*M As* or *Am*) is that condition in which the eye is emmetropic in one and myopic in the other principal meridian.

Compound myopic astigmia (*M As Co* or *M + Am*) is that condition in which the eye is myopic in both principal meridians, but more so in one than in the other.

When in compound astigmia the hyperopia or myopia is relatively so great as to outweigh in importance the astigmia, the condition is more appropriately designated as *hyperopia* or *myopia with astigmia.*

Mixed astigmia (*Ah + Am*) is that condition in which the eye is hyperopic in one meridian and myopic in the other.

Since the kind of astigmia, in accordance with this classification, depends upon the length of the antero-posterior diameter of the eyeball, it not uncommonly happens that *compound hyperopic astigmia* passes by degrees into *simple hyperopic, mixed, simple myopic,* and *compound myopic* astigmia, with the increase in diameter of the eye, as the result of growth or disease.

Symptoms of Astigmia

Of subjective symptoms, subnormal vision, asthenopia and headache are the most characteristic. These are, however, not pathognomonic, for each may occur from some other cause.

Vision in Astigmia.—In the mildest grades of astigmia vision may not be below normal (6/6), and it may even surpass this; but in moderate and high-grade astigmia vision is always defective. The visual power varies, as in other anomalies, under different conditions, and especially with variation in size of the pupil. The latter is a very important consideration, since keratometry shows that corneal asymmetry and irregularities increase rapidly with increase of the distance from the corneal summit. In this way is explained the frequent manifestation of greater astigmia when the examination is conducted under mydriasis than is shown without it.

The question arises as to what is the most favorable relation between the retina and the focal lines, that which one will, as far as possible, seek either by exercise of accommodation or by change in position of the object of vision. In answer to this question, *Javal* has stated, as the result of his investigations, that an astigmope obtains his *best vision when the object is conjugate to the retina in the horizontal meridian;* that is, when the vertical focal line falls upon the retina.

Two advantages arise from this relation: (1) While horizontal lines are more or less blurred, all vertical lines are distinct; and experiment shows that, in reading, distinctness of the vertical strokes of the letters is of more moment than distinctness of the horizontal strokes. (2) The object being in focus in the horizontal meridian, rays of light which would enter in the vertical, ametropic meridian can be largely excluded by partially closing the lids—a device to which astigmopes usually resort, and by which great improvement of vision is gained, especially if the eye is properly adapted in the horizontal meridian.

Reymond and others believe that vision is preferably accomplished in astigmia, not as suggested by Javal, but by adapting the eye first in one and then in the other principal meridian, and that by a rapid change in accommodation a composite mental impression is obtained.

It is possible that this rapid change of accommodation may take place under certain circumstances; in fact, it does apparently occur when a young person affected with hyperopic astigmia is being examined with the clock-face chart. But that this process can be maintained for a long period of time as in reading, or that it can be effective in high astigmia is, I think, entirely beyond the range of probabilities.

Javal's theory is opposed also by *Hess,* who believes that the maximum vision is obtained, not when the eye is adapted in either principal meridian, but when it is so adapted that the retina lies between the two focal lines, at the point *where the intercepted image is free from distortion and where all lines appear equally distinct.*

My experience does not uphold the contention of Hess. I find that while the larger letters are rendered more evenly visible by looking through a lens which places the retina in the position of least confusion, the smaller letters are less recognizable because of the general diffusion than when the vertical strokes of the letters are distinct.

The most unfavorable position of the retina for reading is, according to Javal's theory, such that the letters are in focus in the vertical meridian. The vertical strokes of the letters are then blurred and the horizontal strokes are distinct. Every point of every letter forms on the retina a horizontal line and the horizontal diffusion-image of one letter overlaps that of the adjacent letter, so that the reading of small, closely set type is impossible.

The most favorable position of the retina—adaptation in the horizontal meridian—is possible for distant vision only when the eye is emmetropic in the horizontal meridian or hyperopic with sufficient accommodative power to overcome the hyperopia.

The most unfavorable relation—adaptation of the vertical meridian—cannot be avoided in distant vision when the eye is emmetropic in the vertical meridian, being, in the horizontal meridian, either myopic or hyperopic without accommodative power to render it emmetropic at the expense of the vertical meridian.

In near vision the most advantageous adaptation will be accomplished, as far as possible, by change in position of the object and by exercise of accommodation.

Vision in Irregular Astigmia.—In pathological irregular astigmia defective vision is a constant and characteristic symptom. Objects appear distorted, and sometimes there is monocular diplopia or polyopia. The latter is especially common in irregular crystalline astigmia occurring as a precursor of cataract.

Double or triple monocular vision is not uncommonly observed in ametropia, disappearing with the correction of the ametropia by a suitable lens. Such multiple vision is probably due to slight difference in index of the three main segments of the crystalline lens, so that each segment gives rise to a separate retinal image of an object. In emmetropia these images are so nearly superposed that they are fused as a single image; but when the retina is remote from the position of the average focus (just as in Scheiner's experiment), vision is multiple. This is a frequent symptom in hysterical spasm of the accommodation (*Parinaud*).

Asthenopia.—Astigmopes more often complain of asthenopia than of defective vision. This is especially so as regards the large number of eye-workers—students, accountants and artisans—whom civilization has produced. As with other refractive anomalies, the asthenopia bears no fixed relation to the degree of astigmia. It depends rather upon the state of health and the character of the work pursued.

Headache in astigmia, as in hyperopia, occurs usually in conjunction with asthenopia, but it sometimes occurs without other symptoms pointing to refractive error.

Asthenopia and headache occurring in hyperopia are usually ascribed to exhaustion of the ciliary muscle (*accommodative asthenopia*). In myopia these symptoms are assigned to disturbance in the relation between accommodation and convergence (*muscular asthenopia*). In astigmia either or both of these kinds of asthenopia may arise, but, doubtless, the main source of disturbance is nerve-exhaustion (*retinal asthenopia*) resulting from the mental effort to interpret diffusion-images. It is also possible that in oblique astigmia asthenopia may arise from the tax imposed upon the oblique muscles in their effort to obliterate distortion by rotating the meridians of the eye, as is maintained by *Savage*.

Objective Symptoms.—*The pathognomonic objective*

symptoms of astigmia have already been considered in dealing with objective optometry. In addition to these there are conjunctival congestion (occurring especially after close application of the eyes), chronic conjunctivitis, blepharitis, and congestion of the optic nerve and retina, all of which occur also in other conditions.

Diagnosis of Astigmia

The methods of measuring the degree of astigmia have been given in Chapter X. The order of applying these tests which has been recommended for other refractive errors may advantageously be followed also in astigmia.

The various reasons for the discrepancy which is liable to be found between the ophthalmometric record and the subjective error as determined by the cylindrical correcting lens have been enumerated in Chapter X. In the practical determination of the correcting lens there is still another limitation to the usefulness of the ophthalmometer. This is that it does not reveal any information as to the refraction of the eye in relation to the position of the retina. If, for instance, the instrument records 1 D of direct astigmia, we do not know from this record whether the correcting lens is + 1 D, axis 90 or — 1 D, axis 180. This question has to be decided by other tests.

Of the two other objective methods, *ophthalmoscopy* and *skiascopy*, the former is indispensable in that it informs us whether or not the interior of the eye is in a healthy condition, but as a means of measuring the degree of astigmia it has been entirely supplanted by other tests. Skiascopy, which is the most practically valuable of the objective tests, is especially useful in young children, for it can be applied with considerable accuracy at an age when ophthalmometry and subjective methods cannot be used.

After completion of the objective examination, a careful subjective examination with trial lenses must be conducted. In this examination the indications for cycloplegia are the same as in other refractive errors, for it is to ascertain what degree of hyperopia or myopia is associated with the astigmia that the cycloplegic is employed.

We must note any discrepancy between the astigmia as estimated with cycloplegia and without it. The manifestation of a

higher degree when the pupil is dilated by the cycloplegic usually indicates that the asymmetry is greater peripherally than near the axis. Since in normal vision the peripheral portion of the cornea is excluded, the estimate made without cycloplegia, if corroborated by other tests, is that which should be adopted for the correcting lens.

We sometimes also note a slight difference in the position of the principal meridians as determined with cycloplegia and without it. This difference is probably due to irregularity of the cornea, but it is possible that it is due, as some authorities believe, to an alteration in the crystalline astigmia under the influence of the cycloplegic.

Treatment of Astigmia

The treatment of regular astigmia consists in the correction of the defect by means of a suitable cylindrical or toric lens. In the lower grades correction should embrace the entire error, but in high astigmia total correction will often not be tolerated at first on account of the distorting property of asymmetrical lenses. After a partial correction has been worn for some time the full correction may be ordered.

The annoyance which results from the distortive action of these lenses is usually of short duration in young persons, but elderly persons who have not at an earlier age become accustomed to asymmetrical lenses very often decline to accept correction of their astigmia. This is especially so if the meridians are oblique. It is possible that, as *Savage* believes, the annoyance which is so marked in the correction of oblique astigmia results from the effort of the eyes to overcome the distortion by rotary action (torsion) of the eyes.

The apparent distortion of objects by asymmetrical lenses is due partly to the actual distortion of the retinal image, and partly to the effect exerted by the change in accommodation upon binocular visual perception. The former kind of distortion has been described in Chapter IV. The explanation of the latter kind is the same as that for spherical lenses, for which reference may be made to the chapter on Hyperopia. Of the distorting effect upon binocular vision caused by placing an asymmetrical lens before only one eye, or a much stronger lens before one eye

than before the other, mention will be made in the chapter on Anisometropia.

In astigmia of high degree the correcting lenses should be ordered for constant wear, and preferably so in all astigmia exceeding 1 D. When the astigmia is less than 1 D the correcting glasses may in favorable cases be used only during near work, while in other cases asthenopia will be relieved only if the glasses are worn constantly.

In the correction of astigmia which has been determined with the eye under the influence of a cycloplegic we must be guided by the same considerations as in hyperopia. In other words, we must remember that in a young person accommodative action may modify the relative position of the retina and the focus. Thus an eye which requires during cycloplegia a + .50 D cylinder, may require instead, after the effect of the cycloplegic has worn off, a — .50 D cylinder with its axis at right angles to the axis of the convex cylinder which was formerly accepted. Or if the correction under cycloplegia is a + 1.00 D cylinder it may be necessary to place before this a — .50 D sphere in order to afford clear vision after the cycloplegic effect has passed off.

We must therefore follow the same general rule which was given for the prescription of spherical lenses; that is, we must select the greatest convexity or the least concavity which is compatible with clear distant vision.

Prescription of Compound Lenses.—Since it is the duty of the optician to provide lenses exactly as called for by the prescription presented to him, we must, in ordering correction for hyperopia or myopia associated with astigmia, make use of the knowledge gained in the study of asymmetrical refraction, so that every combination of lenses may be reduced to its simplest form, or to such other form as we may deem preferable.

In our study of this subject (Chapter IV) we have learned that the same refractive effect can be obtained by combining two cylinders at right angles (the crossed cylinder), by combining a spherical with a cylindrical lens, or by using a toric lens. The first of these combinations, *the crossed cylinder,* has no advantages over the other two, and it is not ordinarily used. The second or *sphero-cylindrical combination* is that which is most commonly employed.

In ordering sphero-cylindrical lenses we write the prescription as follows:

R + 2.25 sph. + 1.50 cyl., ax. 75.
L + 1.75 sph. + 2.00 cyl., ax. 105.

The symbol of combination ($\bigcirc$) is sometimes placed between the two lens numbers, but the plus or minus sign is all that is necessary.

In combining lenses we should be familiar with the *principles of transposition.* We readily understand, for instance, that

+ .50 sph. — .50 cyl., ax.. 180° = + .50 cyl., ax. 90°
+ 1.00 sph. — .50 cyl., ax. 180° = + .50 sph. + .50 cyl., ax. 90°
— 1.00 sph. + .75 cyl., ax. 180° = — .25 sph. — .75 cyl., ax. 90°

In the last two examples the cylinder has a smaller numerical value than the sphere; in such cases the combination is equivalent to two homogeneric lenses; that is, *in the simplest form the signs of both component lenses are alike; both are plus or both are minus.*

Therefore when we have a combination with unlike signs, *the numerical value of the cylinder being no greater than that of the sphere,* we transpose the combination as follows: *Subtract the numerical value of the cylinder from that of the sphere, which gives the value of the new sphere, and change the sign of the cylinder, with a change of ninety degrees in its axis.*

If we take another series of examples in which the cylindrical element is the greater, we shall see that if the lenses have different signs, *if the lenses are heterogeneric,* they remain so after transposition. Thus:

— 1.00 sph. + 1.50 cyl., ax. 90° = + .50 sph. — 1.50 cyl., ax. 180°
+ 1.00 sph. — 1.50 cyl., ax. 180° = — .50 sph. + 1.50 cyl., ax. 90°
— 1.00 sph. + 2.50 cyl., ax. 90° = + 1.50 sph. — 2.50 cyl., ax. 180°

In this series of examples the lenses have been reduced to a simpler form by transposition, except the last combination. This has been transposed from a simpler to a less desirable form; that is, from a lighter to a heavier combination.

Unless we have a special reason for doing otherwise, we should write our prescription for any compound lens in its simplest form, because, while the optician would probably have this in stock, the equivalent lens in another form would have to be specially ground.

In the simplest form of a heterogeneric combination the numerical value of the spherical element is not more than one-half of that of the cylinder. Whenever the sphere exceeds this proportion we should transpose the combination in the following way:

Obtain the value of the new sphere by subtracting the numerical value of the old sphere from that of the cylinder; change the signs of both sphere and cylinder and make a change of ninety degrees in the axis of the cylinder.

Prescription of Toric Lenses.—In ordering toric lenses we may write the prescription in the ordinary way, as a sphero-cylinder and add the word, "*Toric.*" The optician will then make the necessary transposition. If we deem it advisable we may also specify the degree of concavity which we desire for its periscopic effect.

Toric lenses are usually made on a base curve of 6 D, more rarely on a curve of 3 D or 9 D. Thus a plano-toric convex lens of 2 D of asymmetry, made on a 6 D curve, would have a curve of + 6 D in one meridian and of + 8 D in the other.

Suppose that we have a case of simple hyperopic astigmia for which we wish to order a toric correction. The 6 D curve is selected and a concavity of — 6 D (spherical) is ground on the inner face of the proper plano-toric lens.

But if in addition to the 2 D of astigmia there is 4 D of hyperopia we should have only — 2 D for the periscopic effect. If this is not deemed sufficient, the 9 D curve should be selected, which would give — 5 D for the periscopic effect.

Surgical Treatment of Astigmia.—It has been proposed to overcome regular astigmia by surgical means—by corneal incisions made at right angles to the meridian of greatest curvature. But the impossibility of regulating the result renders it improbable that this method will come into practical use.

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CHAPTER XIV

ANISOMETROPIA

We have learned that a variation of 1 D in the refraction of the eye corresponds to the minute variation of about one-sixth of a millimeter in the radius of the cornea, or to a variation of one-third of a millimeter in axial length. It is not surprising, therefore, that the refraction of one eye so frequently differs from that of the other eye. It is, in fact, more surprising that any one has exactly the same refractive condition in the two eyes. Yet in many persons there is no difference which can be detected by the means of examination at our disposal. This ideal condition is called *isometropia.**

In a large proportion of persons there is, however, an appreciable difference of refraction in the two eyes. This condition is called *anisometropia.*

While isometropia is the standard or ideal condition, as is emmetropia, and as slight deviation from emmetropia does not constitute a real anomaly, so slight anisometropia is not to be regarded as a pathological state. In other words, anisometropia is a defect only when it is sufficient to cause some disturbance, either visual or nervous. The least refractive difference which we may regard as constituting an anomaly varies with the refraction in the two eyes. For instance, if one eye is emmetropic while the other has 2 D of myopia, there should be no hesitation in classing the anisometropia as a defect, capable of giving rise to very great disturbance; but if one eye has 9 D and the other 11 D of myopia the same anisometropia (2 D) is a subordinate factor.

Anisometropia signifies nothing as to the state of refraction in either eye. One eye may be emmetropic and the other hyperopic or myopic; one eye may be hyperopic and other myopic (*antimetropia*) ; both eyes may be hyperopic or myopic, the degree of error not being the same in the two eyes; or one eye may be

* From ἴσος, equal; μέτρον, measure; and ὤψ, sight.

astigmopic, or there may be a greater degree of astigmia in one eye than in the other.

Etiology.—Anisometropia may be either *congenital* or *acquired,* being more frequently congenital and due to defective development of one eye, with or without involvement of the corresponding half of the cranium. Acquired *anisometropia* results from removal or luxation of the crystalline lens; from alteration of corneal curvature, produced by ulceration or corneal section; from elevation of the retina in partial detachment; or from unequal post-natal increase in size of the eye, as from progressive myopia.

Vision in Anisometropia.—Vision in anisometropia may be accomplished in one of the three following ways: (1) There may be binocular vision; (2) vision may be monocular, either eye being used alternately; or (3) vision may be monocular, one eye being used to the exclusion of the other.

Binocular Vision in Anisometropia.—It having been ascertained by means of the stereoscope or otherwise that an anisometrope possesses binocular vision, the question arises as to the manner in which such vision is accomplished; whether by exercising a greater amount of accommodation in one eye than in the other, or by the mental fusion of the clear image as formed in the adapted eye with the blurred image as formed in the other. The latter and commonly accepted view was disputed in 1889 by *Fick,* who cited a number of cases in evidence of his opinion that the refraction is equalized by unequal action of the ciliary muscle. This theory, which has also been advocated by *Schneller,* is opposed by *Hess,* who from a number of experiments concludes that there is no evidence in favor of unequal accommodation in the two eyes. This question is similar to that of dynamic compensatory astigmia. We have no reason to believe that the ciliary muscle of one eye can be innervated alone, or that when both muscles are innervated, one can receive a designedly greater impulse than the other.*

Alternate Vision in Anisometropia.—This generally occurs when one eye is emmetropic or nearly so, the other eye

*It may happen, however, from an unequal receptivity (irritability) of the ciliary muscles that stimulation of the accommodation-center may give rise to greater contraction of the muscle in one eye than in the other, as is artificially effected by the instillation of eserin in one eye. Similarly, it may be possible that because of unequal sclerosis the same impulse may produce a greater change in curvature of the lens in one eye than in the other.

having 3 D or 4 D of myopia, and both eyes having good visual acuity. Though deprived of stereoscopic vision, the anisometrope who sees in this way enjoys a certain advantage, in that he has good distant vision and yet does not require reading glasses, even though he may have passed the presbyopic age, since the emmetropic eye serves for distant and the myopic eye for near vision.

Monocular Vision with Permanent Exclusion of One Eye.—Vision is accomplished in this way usually when, in addition to the anisometropia, one eye is materially below its fellow in visual power. Strabismus, either convergent or divergent, is the common accompaniment of this condition, convergence being of more frequent occurrence in hyperopia, while divergence is the usual condition in myopia.

Anisometropic Asthenopia.—Since any kind of refractive error is capable of giving rise to asthenopia, it is ordinarily impossible to discriminate between asthenopia due to this cause and that which is directly referable to the inequality of refraction in the two eyes; but that this inequality is of itself capable of producing asthenopia is attested by occurrence of the latter in cases in which one eye is emmetropic and the other slightly myopic if there is *binocular vision*, while no such symptoms occur if the emmetropic eye is used for distance and the myopic eye for near work.

Anisometropic asthenopia is due to *nerve exhaustion* in the effort to maintain binocular vision under disadvantageous conditions. Not only is there indistinctness of images in the unadapted eye, but the images in the two eyes are unequal in size. This inequality may be slight and due chiefly to the diffusion on the retina of the light in the unadapted eye, or the inequality may be very great, as when one eye has been rendered aphakic by the removal of its cataractous lens.

When anisometropia has existed since birth, the eyes may never have learned binocular vision, one eye having passed into a state of strabismus at an early age; or, if binocular vision exists, the nervous mechanism may have become adapted, by training, to the inequality of images. But even in this most favorable condition asthenopia may arise at any time, as when a special tax is thrown upon the eyes, or when the bodily vigor is reduced from any cause.

Treatment.—In the majority of eyes which require the

services of the refractionist the ametropia of one eye will be found to differ slightly from that of the other eye. In all such cases the correction appropriate for each eye should be ordered. It should be our aim also to give the appropriate correction for each eye and thus to restore the normal relationship when the dissimilarity is more marked; but, unfortunately, many persons will not tolerate such correction.

The explanation of this intolerance is found partly in the nerve-disturbance produced when an eye which has previously acted only a subordinate part in vision is suddenly put in condition to co-act with its fellow, and partly in the secondary effects of lenses, such as have been described in previous chapters. In axial ametropia a lens worn at the anterior focus of the eye produces a retinal image equal in size to that formed in emmetropia; hence if both eyes are properly corrected, the images in the two eyes should be of equal size. The disturbance cannot, therefore, be produced in this case by unequal images; it is due to the change from the condition to which the person has become accustomed by lifelong association.

In astigmia the proportions of the retinal image are changed by the correcting lens, but the image cannot be made

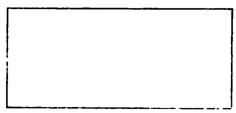

FIG. 105

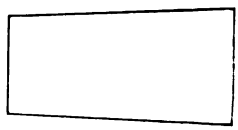

FIG. 106

to conform to that in the emmetropic eye; hence, in monocular astigmia a double difficulty must be overcome when the correcting lens is applied.

The apparent alteration in the size of an object, which has been previously explained (p. 211), produces in anisometropia a one-sided disturbance. This is sometimes a source of great annoyance to persons (architects, mechanics, etc.) who have to deal with the rectangular form of objects. If a rectangular diagram, such as is illustrated in Fig. 105, is placed in front of and equidistant from the two eyes and viewed binocularly with a convex spherical lens before the right eye, the rectangular form of

the object will be lost, the right side appearing broader than the left, as illustrated in Fig. 106. If a concave lens is substituted for the convex lens, the right side of the figure appears smaller than the left. This illusion arises from the fact that the right eye is chiefly concerned in looking at the right side of the object, while the left eye is the more important as regards the left side of the figure. But that the actual change in size of the retinal image is not the sole cause of this phenomenon is shown by the substitution of a cylindrical for the spherical lens. A cylindrical lens, having its axis vertical, produces the same effect as the corresponding spherical lens, and in this case there is no vertical alteration of the image. Hence we must conclude that the apparent alteration is due to disturbance of accommodation. The effort of accommodation which adjusts the naked eye for the left side of the figure is more than sufficient for the right eye, which has a convex lens before it; consequently, the impression is received that the right side is farther away and larger than the left side. Similarly, with the concave lens before the right eye the right side of the figure seems to be nearer and smaller than the left side. The peculiar effect of the cylindrical lens is also explained partly by the influence which it exerts over accommodation and partly by the actual distortion of the image on the retina.

In addition to the foregoing considerations, the prismatic action of lenses is an important factor in the correction of anisometropia. This action is a not uncommon cause of confusion in isometropia, and much more so must it be when, as in anisometropia, the prismatic deviation does not correspond in the two eyes.

All these difficulties apply in anisometropes who have been accustomed to binocular vision without lenses. It is far more difficult to institute binocular vision in those who have contracted the habit of excluding one eye. In the vast majority of such cases it is impossible, except at an early age, to secure binocular vision, and especially is this true when one eye is used for distant and the other for near vision.

When anisometropia results from removal of cataract from one eye while the other eye has good vision, the aphakic eye may be of great service in extending the field of vision and even in entering subordinately into binocular vision; but very rarely will such an eye accept correction by a strong convex lens. This is at

least partly due to the difficulty of avoiding diplopia which tends to result from the one-sided prismatic deviation.

The student will already have concluded that the treatment of anisometropia is attended with much difficulty and uncertainty. The course to be pursued must in every case be adapted to the age and condition of the patient. Childhood is the most favorable age. By the correction of the refractive error of each eye in young children, many eyes which would otherwise become useless are trained to perform their part in binocular vision. If strabismus and inferior visual acuteness are also present, the eye should be aided by stereoscopic or other exercises.

In young adults having binocular vision with anisometropia, the first attempt should be to equalize the refraction, and especially if asthenopic symptoms are present which are referable to the anisometropia. If such correction is not accepted, the symptoms may perhaps be relieved by partial equalization.

It may be stated, as a general rule, that in persons who have reached the presbyopic age without equalization of refraction the correction of anisometropia (except in the lowest degrees) will not be tolerated, and this, whether the glasses are for distant or for near use.

The correction of anisometropia without binocular vision in adults will almost invariably be a thankless task.

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CHAPTER XV

PRESBYOPIA AND ANOMALIES OF ACCOMMODATION

Since the accommodative power undergoes a gradual diminution with advancing years, there comes a time when the amplitude is not sufficient for the reading of small print or for the examination of small objects which must be held near the eyes. We do not often hold our work nearer than 33 *cm* (13 inches). Use of the eyes at this distance requires 3 D of accommodation, and as we can use continuously only about two-thirds of the amplitude, we must have 4.5 D of accommodation in order to be able to maintain comfortable vision at a distance of 33 *cm*.

With 4.5 D of accommodation distinct vision is possible for a short time at *22 cm* (9 inches), and a point at this distance was taken by *Donders* as the critical point in the determination of presbyopia. If the amplitude is not sufficient for distinct vision at *22 cm* when any existing ametropia is corrected, and if the deficiency is due to the physiological sclerosis of the crystalline lens, the eye is affected with *presbyopia*.

The inability of the old man (πρεσβύτης) to see nearby objects clearly was described by *Aristotle,* but he was unable to explain the nature of this condition, which, indeed, was not fully understood until after the elucidation of ocular refraction by *Donders.*

Age at Which Presbyopia Occurs.—Reference to the table (p. 139) shows that the age of forty years is that at which the failing accommodative power reaches the limit of amplitude compatible with close application of the eyes. Shortly after this age—almost always before the forty-fifth year—the onset of presbyopia occurs.

Symptoms.—The most characteristic symptoms of presbyopia are a disposition to hold the book or other work at too great a distance, asthenopia, and, in neglected cases, congestion or inflammation of the conjunctiva.

Diagnosis.—The diagnosis of presbyopia may ordinarily be made without difficulty, in accordance with the age and the inability to read fine print. The static refraction must be first corrected. If the eye is myopic, presbyopia may coexist with good near vision. Hyperopia and astigmia, on the other hand, must be excluded in those cases in which distinct vision is not possible at 22 *cm.*

We must also distinguish between insufficient accommodation resulting from the physiological sclerosis of the lens and that which is due to *weakness* (paresis) *or paralysis* of the ciliary muscle.

Jaeger's Test Types for Determining the Amplitude of Accommodation.—As Snellen's test letters have gained universal recognition for the determination of distant visual acuteness so the test cards of *Jaeger* are everywhere in use for testing near vision. These cards consist of selections of reading matter printed in types of various sizes. No. 1, being the smallest, is intended to be read at 22 *cm* or less. If distant vision is normal while this print cannot be read at the prescribed distance—with the distance correction if the eye is ametropic—deficiency of accommodative power for near work is demonstrated. The larger types are intended for those who from failure of accommodation or from other causes cannot read the smallest print. The nearest point at which the smallest distinguishable type can be clearly seen is the *punctum proximum* (p.p.) or near point of the eye. The distance of this point from the eye ***measures the amplitude of accommodation.***

Oliver's Test Letters.—While well adapted for the purpose for which they were intended, Jaeger's test types are not based upon the visual angle principle, as are those of Snellen. To meet this deficiency *Oliver* has constructed test letters for near vision in conformity with this principle.

Treatment.—The age at which persons seek relief from presbyopia varies with the individual accommodative amplitude and with the character of the work pursued. The average age may be placed at the forty-fifth year. At this age a convex spherical lens of 1 D is the probable correction which will be required. Emmetropes whose work necessitates continuous eyestrain may feel the need of assistance in near work at an earlier age—at any time after the fortieth year.

The average amount of accommodation possessed by healthy persons between the ages of forty and seventy-five years and the probable strength of lens for adapting the eye for continuous near work at a distance of 33 *cm* is indicated in the following table:

Age	40	45	50	55	60	65	70	75
Accom.	4.5 D.	3.5 D.	2.5 D.	1.75 D.	1 D.	0.75 D.	0.25 D.	0
Lens		1	2	2.75	3.25	3.5	3.5	3.5

Although this table serves as a guide, it is not to be blindly followed in individual cases. The appropriate lens must be selected in each case in accordance with the amplitude of accommodation and the distance for which it is desirable that the eyes may be adapted.

When there is normal visual acuteness we seldom find it necessary to prescribe a stronger presbyopic correction than 2.50 D, or 2.75 D, since in ordinary reading and in desk work the full amplitude, as estimated by *Donders,* is not required, and since a stronger correction would entail blurred vision at the distance of ordinary use. Sometimes, however, we are called upon to order the full presbyopic correction for persons who are engaged in very exacting near work, and also for persons whose visual acuity is below the normal standard.

It is apparent that as the strength of the presbyopic lens is increased the range of vision is diminished, since the lenses have

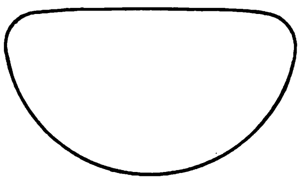

FIG. 107

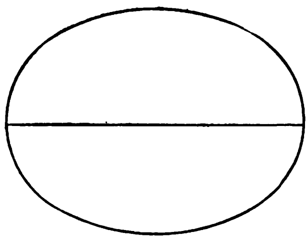

FIG. 108

the effect of producing an artificial myopia, greatly to the detriment of distant vision. On this account elderly people usually acquire the habit of wearing their near-glasses far down on the nose, so that they may look above them during distant vision. A convenient form of glass, sometimes preferred by business men and public speakers is that known as the *clerical lens* (Fig. 107), which has the upper portion cut away.

Bifocal Lenses.—Ametropes who require glasses for distance and other glasses for near use often find convenience in the use of bifocal glasses.

The original split bifocal or *Franklin lenses* consist of two lenses, each properly centered, and separated by a horizontal line (Fig. 108). The upper lens is for distant and the lower lens for near vision. Because of the too restricted field of view for distance, Franklin's invention has been modified by making the dividing line curved (Fig. 109).

Although bifocal glasses may be made in a number of different ways, at the present time there are only two kinds of such glasses in common use. These are: (1) the *cemented bifocal,* in which the presbyopic correction is cemented to the lower part of the distance glass; and (2) *the fused or invisible bifocal,*

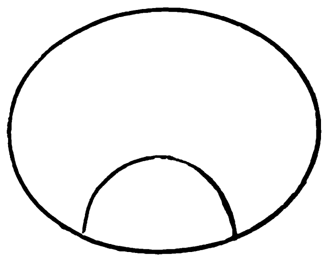

FIG. 109

in which the presbyopic correction of flint glass is embedded in a concavity made in the distance glass of lower index, the two being fused into a solid piece. In making these fused bifocals great care has to be exercised to prevent marring of the curvatures during the process of fusion. If properly made, they are the most satisfactory glasses possible for the ametropic presbyope.

Spasm of Accommodation

Owing to the extreme ease of accommodative changes in childhood, there is in almost all young hyperopes a diminution of the hyperopia effected by action of the ciliary muscle. So accustomed is the young hyperope to exercise this accommodation that he will be unable totally to relax it when the correcting lens is placed before his eye. A certain amount of unrelaxable accommodation is physiological, being due to the *tone* of the ciliary

muscle. The tone of the muscle keeps it in a state of slight contraction. Hence, even in adults the refractive power of an eye is slightly less when tested under cycloplegia than it is when the eye is in its normal condition.

The increase of refraction arising from physiological tone of the ciliary muscle may vary from .25 D to .50 D in the adult to 1 D or more in childhood.

Not infrequently in childhood and early adult life the action of the extremely excitable ciliary muscle transcends the physiological limit, and a condition of cramp or *spasm of accommodation* results. In this state an existing hyperopia may be overcorrected with the production of an apparent myopia.

The effort to overcome hyperopia is not, however, the only cause of accommodative spasm. This may be attributed to astigmia, myopia, overuse of the eyes, insufficiency of convergence, hysteria, and to irritation from the local application of certain drugs (miotics), such as eserin and pilocarpin.

Symptoms.—The symptoms which, when taken in conjunction with the age (childhood and early adult life), are characteristic of accommodative spasm are *inability to see clearly at a distance, asthenopia, headache, macropsia and monocular polyopia.*

Macropsia.—In accommodative spasm a very slight impulse produces an inordinately great accommodative action, and in order to adapt the eye for a certain distance, a much slighter innervation of the accommodative center is requisite than under normal conditions. Because of this unnaturally slight effort of accommodation, objects are supposed to be farther away and consequently larger than they really are. Since the size of an object is judged in accordance with previous experience, macropsia occurs only in recently acquired spasm, such as is occasionally manifested in hysteria (*hysterical amblyopia*), or such as is produced by the instillation of a miotic.

Monocular Polyopia.—This symptom has already been mentioned as occurring in ametropia. The same explanation serves to explain the polyopia which occurs in accommodative spasm, since in this condition the eye is rendered myopic by the excessive action of the accommodation.

Diagnosis.—The diagnosis of accommodative spasm is made in accordance with the above-mentioned characteristics, corroborated by determination of the true refractive condition with

the aid of *atropin-cycloplegia.* In order to ensure relaxation in accommodative spasm the atropin solution (1 per cent) should be used four times a day for several days, or for a week in obstinate cases.

The diagnosis of the cause of the spasmodic action is not always easily made. If the spasm is not due to refractive error, which is by far the most common cause, *hysteria, cerebral lesion,* or other *irritative affection* may be suspected, according to the attendant circumstances.

Treatment.—This consists in removal of the cause, if possible. Any refractive error which may be present must be corrected, and in order that the eyes may adapt themselves to the glasses it may be necessary to continue the application of atropin for several weeks or longer.

Paresis and Paralysis of Accommodation

Weakness of accommodation is a common accompaniment of the general physical debility following severe constitutional diseases; but in addition to this enfeeblement, there is also exerted by certain affections a direct detrimental action upon the nerves of accommodation.

Diphtheritic Paralysis.—This may consist in diminution (*paresis*), or in complete abolition (*paralysis*) of the accommodative function. In such cases the diphtheritic toxin produces a *peripheral ciliary neuritis.* The inflammation also frequently affects other branches of the third nerve, causing *ptosis* and *divergent strabismus.*

Diphtheritic paralysis is not confined to the third nerve; the palatal muscles are also frequently affected. Paralytic symptoms occur after subsidence of the febrile stage, usually in the second or third week of convalescence. Complete recovery follows usually in about a month.

Syphilitic Paralysis.—This results from injury to the nerves or their centers by gummatous deposit or degeneration. Accommodation may be paralyzed without involvement of the iris, or there may be both cycloplegia and mydriasis (*internal ophthalmoplegia*), with or without paralysis of the external ocular muscles.

Paralysis Caused by Non-syphilitic Brain Lesion.—Paresis or complete paralysis of accommodation may also result

from *alcohol or tobacco poisoning,* from *meningitis, brain tumor,* or other cerebral affection. Here, as in syphilitic nuclear disease, there may be cycloplegia with or without mydriasis, and with or without involvement of the extra-ocular muscles.

Glaucomatous Paralysis.—The abnormally great pressure upon the ciliary nerves in glaucoma produces a paralytic state of these nerves, with a consequent deterioration of accommodative function.

Accommodative Paralysis Arising from Other Diseases.—Various diseases, as *diabetes, rheumatism, gout, lithiasis,* and also severe contusions sometimes exert a direct action upon the accommodative apparatus, causing an abridgment or abolition of function.

Artificial Cycloplegia.—We have already learned that the instillation into the conjunctival sac, or the internal administration of large doses, of *atropin* and similar drugs produces paralysis of accommodation and mydriasis (Chapter X).

Symptoms and Diagnosis of Accommodative Paralysis.—The most characteristic symptom of accommodative paralysis is, except in myopia, the *inability to see near objects clearly.* As macropsia occurs in spasm of accommodation, so *micropsia* is a not uncommon manifestation of cycloplegia. The attendant mydriasis may give rise to dazzling, dizziness, and nausea.

The diagnosis is made by ascertaining the amplitude of accommodation and excluding presbyopia. The amplitude may be determined with Jaeger's test types and, if the pupil is moderately dilated, by skiascopy. If, after the static refraction has been ascertained, the person under examination is directed to look at an object placed near the punctum proximum of cenvergence, the examiner may decide in accordance with the principles of skiascopy whether the eye becomes myopic through exercise of accommodation, and, if so, to what extent.

Treatment of Accommodative Paralysis.—The treatment depends upon the cause of the paralysis, which must be determined, if possible. Hygienic and tonic treatment for the debilitated, mercury and iodides for syphilis are evident indications. In chronic non-syphilitic brain lesions not much can be done. If mydriasis coexists, and especially in artificial cycloplegia, dazzling must be prevented by the use of tinted glasses.

Loss of Accommodation from Absence or Luxation of the Lens.—Accommodation is clearly impossible when the crystalline lens is absent from the eye, for the most energetic contraction of the ciliary muscle does not increase the curvature of the cornea to a degree capable of measurement with the ophthalmometer. The apparent accommodation which sometimes occurs in such eyes is due to contraction of the pupil and to unusual ability to interpret diffusion-images.

In luxation of the lens the condition resembles aphakia if the lens does not lie in the pupillary space. On the other hand, in partial luxation, the refractive power of the eye is usually increased.

The following authorities have been consulted in the preparation of the foregoing chapter:

Donders, *Anomalies of Refraction and Accommodation;* and *Ueber scheinbare Accommodation bei Aphakie,* Arch. für Ophthal., 1873.

Aristotle, *Opera* (Didot's Greek-Latin Ed.), *Prob.,* sec. xxxi.

Landolt, *Refraction and Accommodation of the Eye.*

Weeks, *Intra-Ocular Muscles,* Posey and Spiller's *Eye and Nervous System.*

Jaeger, *Schrift Scalen.*

Oliver, *New Series of Metric Test Letters and Words for Determining the Amount and Range of Accommodation.* Tr. Am. Ophth. Soc., 1885, and Med. News, 1886.

PART IV

DISORDERS OF MOTILITY

CHAPTER XVI

OPTOMETRY OF THE MOTOR APPARATUS

Before entering upon the details of the methods of determining the condition of the muscular apparatus of the eyes we must become familiar with the various terms which we shall have occasion to use in dealing with this subject. Some of these have already been mentioned in Chapter IX.

We are indebted to *Stevens* for the modern nomenclature of the muscular equilibrium of the eyes. He uses the following classification:

(1) *The relation of the visual lines to each other.*

(2) *The relation of the normal visual planes to the cranium.*

(3) *The relation of the vertical meridians to the cranium.*

(4) *Spasmodic affections of the eye muscles from functional causes.*

(1) The study of the first relation will occupy the greater part of our attention. As regards this relation *orthophoria* (ὀρθός, right; φορά, a tending) is the ideal condition. Orthophoria is defined as *a tending of the visual lines in parallelism,* the determination being made for a point not less than six meters distant. In orthophoria the visual line of each eye passes through the distant point of fixation, even when one eye is excluded from vision, as by covering it with a card.

Deviation from orthophoria may be either *latent* or *manifest.* A latent deviation is called *heterophoria*; a manifest deviation is called *heterotropia.*

In heterophoria there is binocular vision, but when one eye is excluded from vision its visual line undergoes a deviation. In accordance with the direction of this deviation there results

esophoria, deviation inward; *exophoria,* deviation outward; *hyperphoria,* deviation upward; and *hypophoria,* deviation downward. Similarly a deviation inward and upward constitutes *hyperesophoria*; a deviation downward and outward is *hypo-exophoria,* etc.

In heterotropia vision is monocular and one eye deviates even when uncovered. In accordance with the direction of deviation heterotropia is subdivided into *esotropia, exotropia, hypertropia, hypotropia* and their compounds.

Heterotropia is also called *squint* or *strabismus. Esotropia* is *internal* or *convergent* strabismus; *exotropia* is *external* or *divergent* strabismus; *hypertropia* is strabismus *sursumvergens;* and *hypotropia* is strasbismus *deorsumvergens.* The latter two of these terms, being less simple than the terms of the newer nomenclature of Stevens, are gradually falling into disuse, but *convergent* and *divergent strabismus,* which are very expressive, remain in favor.

There are two essentially different kinds of heterotropia: *concomitant* or *comitant,* in which the deviation remains the same in the various directions of the gaze; and *paralytic,* in which the deviation changes as the direction of the gaze is altered.

Comitant deviations are divided into: (*a*) *alternating,* when sometimes one eye and sometimes the other deviates; and (*b*) *monocular* when the deviation is always confined to the same eye.

Another division is: *intermittent* or *periodic;* and *constant* or *continuous.*

(2) *As regards the relation of the visual plane to the cranium, there are five possible conditions.*

(a) *Euthophoria,* the ideal condition, is that in which the passive adjustment of the visual plane coincides with the plane of the horizon, or very nearly so.

(b) *Anophoria* is that condition in which the passive adjustment of the visual plane is decidedly above the horizontal plane.

(c) *Katophoria* is that condition in which the passive adjustment is decidedly below the visual plane.

(d) *Anotropia, and* (*e*) *katotropia* bear the same relation to anophoria and katophoria as heterotropia does to heterophoria; that is, anotropia and katotropia are manifest errors, whereas anophoria and katophoria are tendencies, not deviations.

(3) *As regards the relation of the vertical meridians to the cranium,* the ideal condition is such that the normal vertical meridian of each eye remains vertical in passive adjustment. Any deviation from this condition is *declination* (*Stevens*); or *cyclophoria,* or *cyclotropia* (*Savage*).

(4) *Under the head of spasmodic affections we consider nystagmus.*

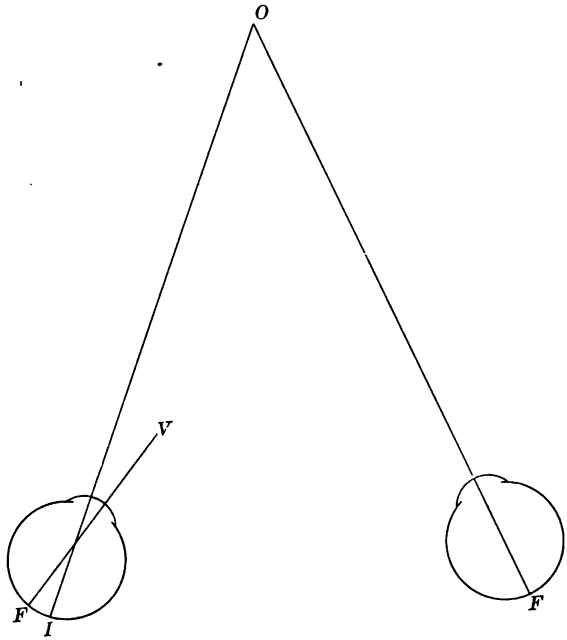

FIG. 110
Showing the position on the retina of the false image (*I*) in strabismus.

Diplopia.—We know that distinct vision is possible only when the image falls upon the fovea, and that the normal fusion into a single perception of the two visual impressions is possible only when the image falls upon the fovea of each eye. When the two visual lines do not meet at the object of vision one eye (*the fixing eye*) will be so directed as to receive the image upon its fovea, while the other eye receives the image upon an eccentric part of its retina, and at the same time some other external object casts its image upon the fovea of this eye. Under experimental conditions we can see the two objects whose images are formed on the

two foveas, as when a part of a familiar picture is made with a stereoscope to fall upon the fovea of one eye and the complement of this picture is made to fall upon the fovea of the other eye. Thus, the image of a horse being presented to one eye and that of a man in the attitude of rider to the other eye, we form the mental picture of the rider upon the horse. But in ordinary vision the

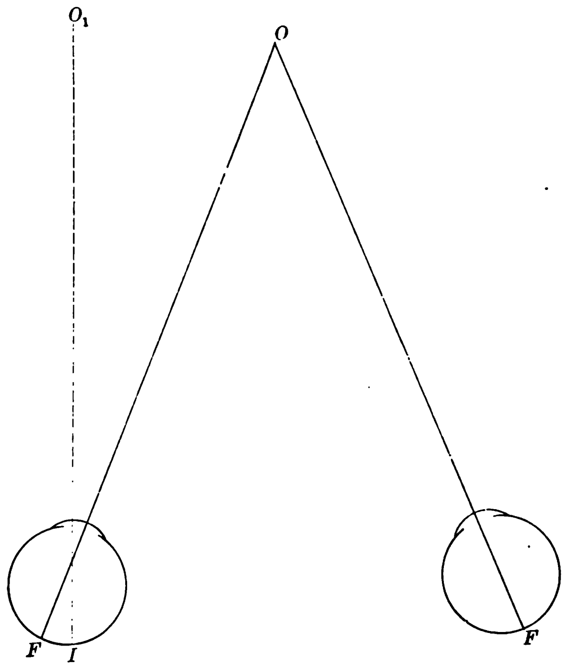

FIG. III
Projection (I O) of the false image.

image which falls upon the fovea of the deviating eye will be disregarded, while the eccentrically placed image of the object which the other eye is fixing will be manifested to consciousness as the second image of the object of fixation. This is ***binocular diplopia.*** Two images of the object of vision are seen: one, *the true image,* is formed upon the macula of the fixing eye; the other, *the false image,* which is less distinct, is formed on a part of the retina of the deviating eye more or less removed from the macula.

Orientation of the False Image.—In convergent strabismus the deviating eye receives the image of the object of fixation upon a part of the retina which is situated on the nasal side of the fovea (Fig. 110). *In normal vision* this part of the retina could be stimulated only by an object situated on the temporal side of the object of fixation (Fig. 111). The subject of strabismus therefore not being able to readjust the nerve associations, *assigns such position to the object of vision as an object stimulating the same part of the retina would have if perceived through an eye in its normal position.*

In convergent strabismus, the nasal side of the retina being stimulated in the deviating eye, the false image is displaced to the *temporal* side; that is, to the *right* side if the *right* eye deviates inward, and to the *left* side if the *left* eye deviates inward. The true image being seen in its correct position, the false image appears (relatively to the true image) to lie on the side corresponding to the deviating eye. This is called *homonymous diplopia.*

In divergent strabismus the opposite condition occurs. The false image lies on the *temporal side* of the retina and it is projected towards the *nasal side.* It thus appears to be on the side opposite to the deviating eye. This is *crossed diplopia.*

Similarly, *in hypertropia* the false image of the *higher eye* appears *to be lower* than the true image of the fixing eye.

The displacement of the false image is always in the direction opposite to that of the false position of the eye. When the eye turns up the false image is accordingly lower than the true image of the other eye, and when the eye turns down the false image is higher than the true image. So also when there is *extorsion* of the vertical meridian of the eye there is *intorsion* of the corresponding image and *vice versa.*

Primary and Secondary Deviation.—When one eye is used for fixation while the other squints, the angular deviation of the squinting eye constitutes the *primary deviation.* When the fixing eye is covered and the squinting eye moves into the fixation position while the other eye now deviates the resulting deviation of the good eye constitutes the *secondary deviation.*

Breadth of Fusion.—Since a prism interposed between an eye and the point of fixation changes the path of the light which enters the eye from this point, it is apparent that if in binocular

fixation we place a prism before one eye the light which enters the eye through the prism does not fall upon the macula of this eye and in consequence of this diplopia results. But so great is *the natural desire to avoid diplopia* and to secure binocular vision that as far as the eye is able to do so, it quickly readjusts its position and assumes that direction which causes the image to fall upon the macula. The strongest prism which can thus be overcome for the accomplishment of binocular vision measures *the breadth of fusion.*

The fusion power varies greatly in different directions. It is greatest in convergence. We can, by the interposition of prisms see a distant point of light singly while the eyes behind the prisms are exercising a convergence of 7 *ma* or even more. This amount of convergence is necessary to overcome the action of a prism of about 25△ before each eye. It is apparent that the bases of the prisms must be placed *out,* towards the temples, in order that the point of fixation may be displaced nasalward, as is required for binocular fixation of a distant point with the eyes in convergence. Prisms having their bases towards the temples are therefore called *converging prisms.*

Similarly, it is apparent that prisms with their bases *in,* towards the nose, diminish convergence or cause an actual divergence of the visual lines. Such prisms are called *diverging prisms.* The normal breadth of fusion in divergence is about 1 *ma,* as represented by a prism of 3½△ before each eye.

In the vertical meridian the breadth of fusion is less. Only a very weak prism (about 3△ base up or down) can be interposed between the eye and the fixation point without producing diplopia.

There still remains to be mentioned the power of *rotating the retinal meridians* for the avoidance of diplopia. This question has been studied chiefly by *Stevens* and by *Savage.* Both authors agree that the breadth of fusion for a vertical line is considerably greater than that for a horizontal line. According to Stevens the amplitude of rotation without diplopia is, for a *vertical line,* about 10° *in or out,* or slightly more out. For a *horizontal line* he assigns 3° *up or down* as the normal amplitude.

Artificial Diplopia.—When the strength of the prism which is interposed between the eye and the point of fixation is greater than the amplitude of fusion, *insuperable diplopia* results. We make use of this phenomenon, that is, we create an artificial diplo-

pia, in most of our methods of determining the muscular equilibrium of the eyes. When the diplopia can no longer be overcome the non-fixing eye presumably assumes its *position of equilibrium* as determined by the muscular adjustments under a minimum of innervation.

Tests Used in Motor Optometry

Of the various methods available in this branch of optometry some are *subjective,* others are *objective.* The two groups of tests are, however, more closely associated than the corresponding groups in refractive optometry, in which we learned to employ first one group and then the other. In motor optometry we do not make this distinction. We proceed in a routine manner, using subjective and objective tests in any order which may be convenient. For instance, it is a logical procedure to measure first the converging power and next the diverging power of the muscles. The former measurement may be made objectively, while the latter must be made by means of a subjective method.

Cover Test.—The simplest method of testing the muscular equilibrium consists in covering one eye, while the other eye is directed towards some point of fixation, and watching the behavior of the eye at the moment of its uncovering.

In making use of this method for determining the muscular equilibrium we direct the person undergoing examination to look at a distant point of light. If, while he performs fixation with one eye, the other eye, at the moment of uncovering, makes a movement of redress in order that it also may perform fixation, we know that binocular vision exists, and that there is a deviation from orthophoria. If the movement is inward, the eye has deviated outward under cover, and there is a condition of *exophoria.* If, on the other hand, the eye moves outward on being uncovered, there is *esophoria.* If it moves downward, there is *hyperphoria.* If it moves upward there is *hypophoria,* that is, there is *hyperphoria* of the other eye.

If, when the eye is uncovered there is no movement of redress, there is *orthophoria,* or else the eye does not perform fixation, vision being monocular and accomplished with the other eye.

When vision is monocular the muscular error is manifested as strabismus, which, as a rule, the examiner may detect by visual

inspection. We then use the cover test to ascertain whether the strabismic eye is capable of fixation. For this purpose we cover the fixing eye, and note whether the other eye moves into the fixation position.

We may approximately estimate the degree of imbalance by observing the strength of the prism which is required to annul the movement of redress, but as it is difficult to observe a very slight movement of the eye, other tests are more convenient for this purpose.

Duane's Parallax Test.—This test is another method of applying the cover test; but instead of using it as an objective test and observing the movement of redress, we request the examinee to say whether, as a card is passed quickly from one eye to the other, there is an apparent movement of the distant point of light. If the light appears to move to the *right* when the *right* eye is uncovered, there is homonymous diplopia (inward deviation); if it moves to the left when the *right* eye is uncovered there is *crossed diplopia* (outward deviation), and so on. The prism which annuls the apparent movement corrects the deviation. In practice it is better to increase the strength of the prism until a slight movement commences in the opposite direction. The prism which has this effect is about 2Δ stronger than the prism which corrects the deviation. (*Duane.*)

Colored Glass Test.—When a colored glass is placed before one eye the impulse for binocular vision is materially reduced, and in marked heterophoria two images of a flame, one of them colored by the glass and the other the natural color of the flame, will be seen. In applying this test we generally use the red or the cobalt blue glass of the trial case, and have the examinee look at a candle flame or other small light at a distance of five or six meters. We then determine the kind of heterophoria present from the relative position of the double images.

This method is very convenient in demonstrating the coexistence of lateral and vertical imbalance, such as *hyper-esophoria* and *hyper-exophoria,* but it is not very accurate for the measurement of the amount of heterophoria, for if we attempt to measure the displacement of the false image by the prism which superposes it upon the true image, we find that when the two images are brought near together they are fused by the impulse for binocular vision.

Graefe's Test.—*Graefe's* test consists in the production of insuperable diplopia by means of a prism. Since under this condition binocular vision is impossible, the subject of examination makes no effort, or, at the most, a very slight effort, to adjust the muscular apparatus for single vision.

To test the lateral equilibrium we place a prism of 8 △ or 10△, with its base down, before one eye of the examinee, while he looks at a point of light at a distance or five or six meters. Because of the diplopia created by the prism two images of the light will be seen. Since the base of the prism is down, the false image will be the higher; and if there is *orthophoria* as regards the lateral equilibrium *the two images will be in the same vertical*

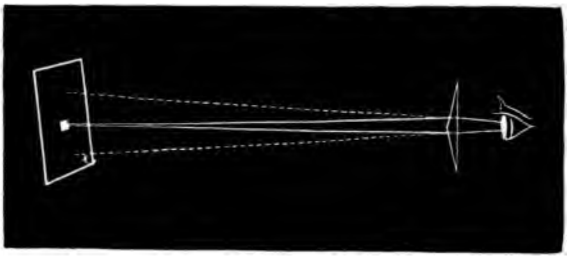

FIG. 112

line. If there is *esophoria* the false image will lie on the side corresponding to the eye which has the prism before it (*homonymous diplopia*); if, on the other hand, there is *exophoria* the false image will lie on the opposite side (*crossed diplopia*). The prism which annuls the lateral displacement measures the heterophoria.

Maddox recommends, as easier of accurate application, the double prism (Fig. 112). This is placed before one eye so that the double base line bisects the pupil. Two images are then seen with this eye. In testing the lateral muscles the base of the prism is horizontal, and one image is vertically over the other. In orthophoria the single image seen with the other eye lies between the double images and in the same vertical line with them. In lateral heterophoria the middle image is not in the same vertical line with the other two images, and the prism which brings all three images into the same vertical line measures the heterophoria.

In measuring the vertically acting muscles the base of the prism is vertical, and the three images lie in the same horizontal line in orthophoria. In hyperphoria the middle image is not in

the same horizontal line with the other two images, and the prism which brings all three images into the same horizontal line measures the hyperphoria.

In applying this test for finding the vertical equilibrium we place a prism of 10△ with its base in before one eye, and, as

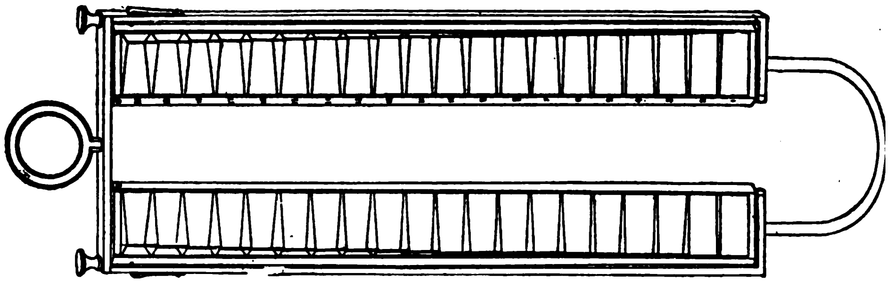

FIG. 113
Prism Bar.

before, have the patient look at a distant point of light. If there is no heterophoria in the vertical direction the two images will lie in the same horizontal plane; but if one eye tends to a higher plane than the other eye, the image which corresponds to the *higher* eye will be the *lower,* and *vice versa.* We measure the degree

FIG. 114
Rotary Prism.

of hyperphoria by the prism which places the two images in the same horizontal plane.

In the application of Graefe's test we may select the proper prism from the trial case; or we may use a *prism bar* (Fig. 113) or a *rotary prism* (Fig. 114), but the most convenient apparatus is the *phorometer of Stevens* (Fig. 115). This consists of a pair

of prisms, each of 5△, suitably mounted upon a bracket or stand, and so arranged that by rotating one prism a corresponding motion is conveyed to the other. By this means, when the base of one prism is directly *up* (towards the brow) the base of the other is directly *down;* when the base apex line of one prism is horizontal that of the other is likewise horizontal, both bases being *in* (towards the nose) or both being *out* (towards the temples). In testing the lateral muscles vertical diplopia is produced by placing the base of one prism up and that of the other prism down. If

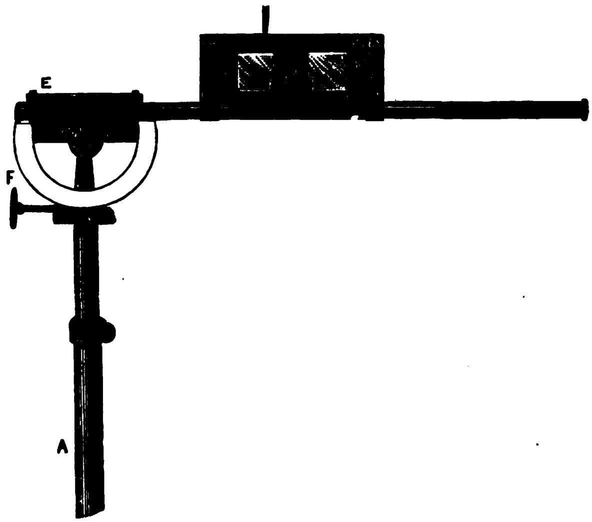

FIG. 115
Stevens Phorometer

the double images do not appear in a vertical line, there is esophoria or exophoria. By rotating the prism the images are shifted so that one of them lies directly over the other, the degree of imbalance being indicated on a scale in accordance with the amount of rotation required. In testing the vertically acting muscles the prisms are rotated into the horizontal plane for the production of lateral diplopia, when any existing hyperphoria will be manifested by one of the double images being higher than the other. The degree of imbalance can be ascertained by rotation of the prisms until the two images lie in the same horizontal plane.

Maddox Rod Test.—The Maddox rod consists of a small glass cylinder, or a series of parallel cylinders (Fig. 116), mounted

in an opaque diaphragm of suitable size to be placed in a trial frame. The cylinder produces very great magnification of images in the direction at right angles to its axis, so that a small flame as seen through this cylinder appears as a long streak of light. Hence, if the cylinder is placed, with its axis horizontal, before

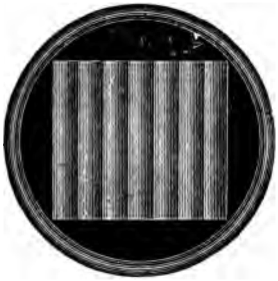

FIG. 116
Maddox Rod.

one eye while a small light is viewed binocularly, the vertical streak, as seen with one eye, cannot be fused with the flame as seen with the other eye, and in the abandonment of the attempt to effect fusion the eyes assume their position of equilibrium. If the streak of light appears to pass vertically through the flame,

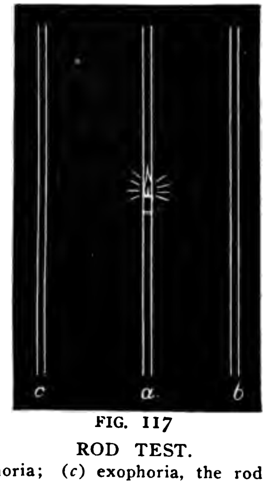

FIG. 117
ROD TEST.
(*a*) Orthophoria; (*b*) esophoria; (*c*) exophoria, the rod being before the right eye.

there is no disorder of lateral equilibrium; if the streak is displaced homonymously, there is esophoria, and if there is crossed displacement the condition is that of exophoria (Fig. 117). The

prism which causes the streak to pass vertically through the flame measures the lateral heterophoria.

If we place the rod vertically the streak of light appears in the horizontal direction. If there is no vertical heterophoria the streak passes through the middle of the light. If there is hyperphoria of the eye before which the rod is placed the streak is below the light, and if there is hypophoria of this eye (hyperphoria of the other eye) the streak is above the light. The prism which causes the streak to pass horizontally through the light measures the hyperphoria.

Stenopaeic Lens Test (*Stevens*).—A strong convex lens (13 D) is covered by an opaque disk having a small, circular opening at its center (Fig. 118). If one looks through this aperture, a distant flame appears as a circular blur of light (Fig. 119). If the muscles are normally balanced, the flame, as seen

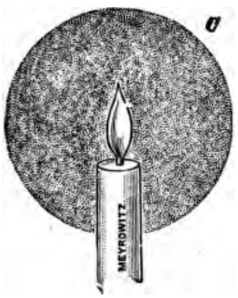

FIG. 119
Orthophoria

FIG. 118
Stenopaeic Lens

FIG. 120
Heterophoria

by the fellow-eye (which is uncovered), will appear to be at the center of the blurred image. In heterophoria the clear image will not lie at the center of the field, but will be displaced in accordance with the kind and degree of muscular error, which is measured by the prism required to bring the image of the flame into the center of the field.

Measurement of Convergence and Divergence.—A ready method of measuring the converging power consists in having the examinee look at the point of a pencil, which we hold in the median plane, while we gradually move the pencil nearer to his eyes until we see one eye abandon the effort to maintain fixation and turn outward. The position of the pencil when this

occurs marks the *near point of convergence.* If the amplitude is normal, convergence can be maintained until the pencil is about four inches (10 *cm*) from the eyes.

If we wish to make an accurate measurement in meter angles we use the *ophthalmo-dynamometer of Landolt* (Fig. 121).

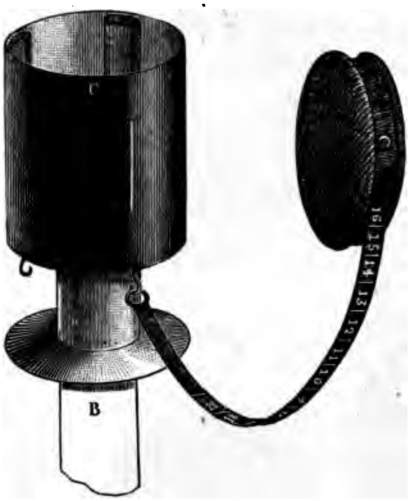

FIG. 121
Ophthalmo-dynamometer.

We measure the diverging power by means of prisms. If we place a prism with its *base in* before one eye, light from a distant point can fall upon both foveas only when the visual lines are divergent. Therefore, the strongest prism with which binocular vision can be maintained measures the diverging power. The average normal diverging power is represented by a prism of 7△ (*base in*) before one eye; or by a prism of 3½△ before each eye. *This corresponds to* 1 *ma of divergence,* as reckoned upon an interocular base line of 64 *mm.*

Measurement of Prism Convergence.—Prism convergence has already been described as the *breadth of fusion* in convergence. We have learned that this may reach 7 *ma.* Such an amount, however, is nót usually manifested at the first examination. But the increase of the fusion power which results from training does not signify that the muscles have been strengthened by practice. It means only that the person has learned to con-

verge for a distant object just as if the object were very near the eyes.

The term *adduction* was improperly applied by *von Graefe* to express prism convergence, and *abduction* was with equal impropriety used to express divergence. These misnomers remain in common use. In accordance with the definitions already given adduction refers to any rotation of the eye inward, and abduction to any rotation outward, as in the movement of both eyes to the right or to the left.

Measurement of Strabismus

The following tests are used in the measurement of heterotropia or strabismus.

Graefe's Linear Method.—This method is suitable only for horizontal deviations, which we can measure approximately in the following way if the squinting eye is capable of fixation. The patient is directed to look at a distant object with the better eye while the point where the vertical line passing through the border of the cornea cuts the lower lid is marked in ink. The better eye is then covered and the deviating eye moves into position for fixation. The point where the corresponding vertical line cuts the lower lid is again marked, and the distance between the points measures the strabismus (Fig. 122). In an eye of normal size

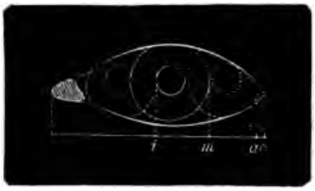

FIG. 122

Linear Measurement of the Lateral Excursions of the Eye (*Alfred Graefe*).

each millimeter of displacement corresponds to an angle of deviation of about five degrees.

This test has been criticised because the measurements are made from the linear displacement of the cornea and not from the actual rotation in degrees of the eye. We should remember, however, that the principle of this method is the same as that of the tropometer, which is usually regarded as furnishing one of the most accurate methods available for measuring ocular rotations.

Graefe's method is therefore a rational and useful test for the ready and approximate measurement of strabismus. The advantage of the tropometer is that it enables us to make the observations much more accurately and that it is applicable for measurements in other directions besides the horizontal plane.

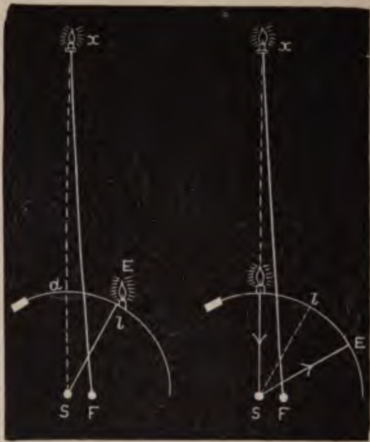

FIG. 123 Javal's Method. FIG. 124 Charpentier's Method.

When the squinting eye is not capable of fixation we can make a rough guess as to the deviation by comparing the horizontal distance of the pupillary center from the inner canthus with the corresponding distance in the fixing eye.

The Perimeter Method.—In measuring the strabismus with the perimeter by *Javal's* method the squinting eye is placed at the center of the arc, while the fixing eye is directed to a distant point, as a candle light five or six meters away (Fig. 123). A distant fixation point is taken in order that the effect of converging for a near point may be avoided. While the patient looks at the light the examiner moves another small candle flame (or an electric light) along the arc of the perimeter until he, *being directly behind the flame,* sees the corneal image in the middle of the pupil of the squinting eye. The error which is due to the fact that the visual line does not usually pass through the center of the pupil is not sufficient to require correction. This method is accurate, but when the strabismus is slight it is difficult or impossible for the examiner

to place his head in the proper position without cutting off the patient's view of the fixation light.

This difficulty is avoided in *Charpentier's method,* which, however, is otherwise inferior to Javal's method. Charpentier's method is illustrated in Fig. 124. As in Javal's method, the patient looks at a distant candle light, but in this method the second candle flame is placed at the fixation spot of the perimetric arc, while the examiner moves his eye along the arc until he sees the reflected image of the candle flame in the middle of the pupil of the squinting eye. We see from the diagram that the angle which his position marks on the perimetric arc is twice the angle of deviation.

Priestly Smith's Tape Method.—Instead of measuring the deviation on the arc of a perimeter we may use a *tangent scale,* the markings of which correspond to degrees of rotation at the specified center. *In Priestly Smith's method* (Fig. 125) two pieces of tape are used. The first of these is one meter long, and it is stretched between the patient and the examiner for the purpose of maintaining the proper distance between them. The second

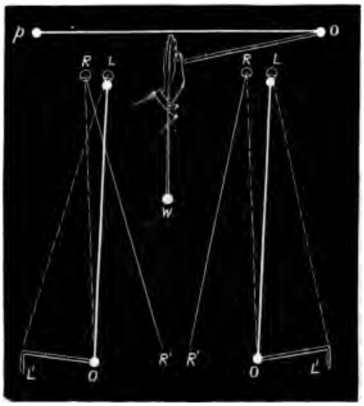

FIG. 125
Priestly Smith's Tape Method.

tape is graduated in tangents of degrees on a one meter radius. The two pieces of tape are attached to a ring placed on a finger of the examiner's hand—the hand in which he holds the ophthalmoscope for obtaining the corneal reflections. He then takes the free end of the graduated tape lightly between two fingers of the

other hand, at which the patient is directed to look. He moves this hand until he sees the image in the center of the pupil of the squinting eye, when he reads from the tape the number of degrees of deviation. This is a simple and easy method, but it assumes that the rotation of the squinting eye is the same as that of the fixing eye. *This is not true in paralytic strabismus.*

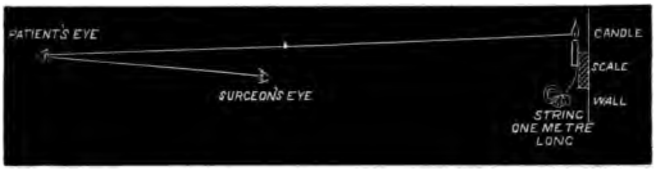

FIG. 126
Tangent Strabismometery (*Maddox*).

Maddox Tangent Scale.—*Maddox's* method is based upon that of Priestley Smith. It is a more convenient way of applying the tangent scale principle. The patient is placed facing a candle flame at the meter-distance, while the examiner places his head between the patient and the candle, but at a lower level so as not to cut off the latter's view of the candle (Fig. 126). The patient

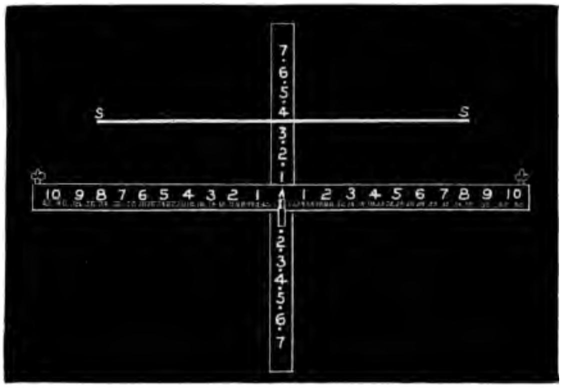

FIG. 127
Tangent Scale (*Maddox*).

is then directed to look at successive figures on the scale until the corneal reflex appears in the center of the pupil of the squinting eye. The degree of deviation is marked by the number at which the patient must look in order that the desired appearance may be obtained. The tangent scale is shown in Fig. 127.

Worth's deviometer consists of a Maddox tangent scale arranged in a way suitable for examining young children. It carries a movable electric lamp, which can be quickly lighted and extinguished so as to attract the attention of the child to any part of the scale at the will of the operator.

Measurement of the Field of Fixation.—To these various tests for measuring strabismus we must add the measurement of the field of fixation, which is of very great importance, especially in paralytic affections.

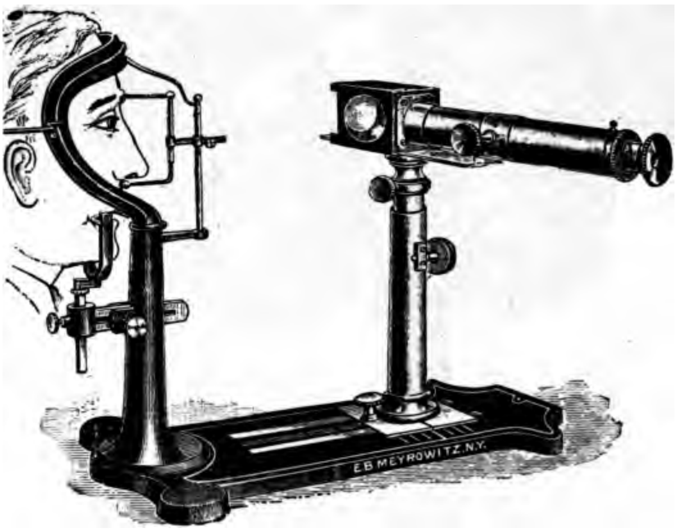

FIG. 128
Stevens Tropometer

We may roughly measure this field by carrying a pencil about in the various directions of the gaze while the patient follows its movements. In case of marked limitation of movement we can easily see that the affected eye does not follow its fellow as it does under normal conditions. But for the exact determination of the ocular rotations we use either the *perimeter* (or the tangent scale) or the *tropometer.*

The chief advantage of the tropometer is that it eliminates the necessity of the examiner's placing his head in inconvenient positions, as is required in objective measurements with the perimeter, and that the projection of the nose does not interfere with

the measurement of extreme inward rotation, as it does in the use of the perimeter.

In using the perimeter for measuring the field of fixation we place the eye to be examined at the center of the arc and note the greatest rotation possible. We may do this in either of two ways.

FIG. 129
Worth-Black Amblyoscope

In the first or *subjective* method the test object consists of small reading matter which cannot be seen in indirect vision. The farthest point on the arc to which this can be removed while it can be distinguished marks the rotatory power in the specified direction. In the second or *objective method* we use a candle or other light and note the greatest degree of rotation which can be made while we see the corneal reflex in the fixation position.

The tropometer of *Stevens* (Fig. 128) consists of a telescope arranged with a reflector so that the tube of the telescope is at right angles to the examinee's line of vision. There is also a head rest to prevent motion of the head. The measurements are made by means of a scale in the eye piece, in the construction of which it is assumed that the position of the center of rotation does not differ much from that of the normal eye.

In using the tropometer we first adjust the scale while the

examinee looks into the center of the instrument; we then note the degree marking on the scale when he turns his eye as far as possible in the direction under consideration.*

Tests of Binocular Vision.—We may under ordinary circumstances assume that vision is binocular when our tests reveal binocular fixation. But when one eye is much inferior to the other in visual acuity, the inferior eye may perform fixation and enter subordinately into the visual process without the accomplishment of true stereoscopic vision. Again, in certain cases of long-standing strabismus in which central fixation is not possible with the squinting eye, the false image in this eye is apparently blended with the true image of the other eye. But in this case also stereoscopic vision does not exist. We must therefore in all cases of strabismus take means to ascertain whether stereoscopic vision exists, for if it does not, we should, except in evidently hopeless cases, endeavor to institute the performance of this function.

Hering's test with falling bodies is well known, but the one test upon which we now rely is that with the stereoscope. *Worth's*

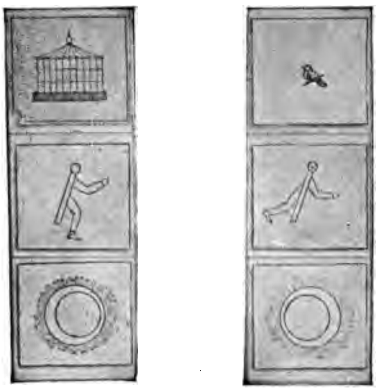

FIG. 130
Test Pictures used with the Amblyoscope

amblyoscope, with the improved mechanical adjustments which have been added by *Black* (Fig. 129), furnishes the most convenient form of stereoscope for ascertaining whether or not binoc-

*This scale has been incorrectly described by some writers as a *tangent scale.* Such a scale would give erroneous results, for it is the chord of the arc of rotation, not the tangent, which we measure. The scale, as constructed in the *Stevens tropometer,* is a *scale of sines.*

ular vision exists. The rings shown in Fig. 130 are typical of the diagrams which are used in testing the sense of perspective. When these rings are fused in single vision they give the impression of a hollow cylinder.

Tests for Cyclophoria

If, with one eye closed, we hold before our other eye a double prism, *so that its double base-line bisects the pupil,* and then look

FIG. 131
Cyclo-phorometer (*Savage*).

through the prism at a horizontal black line on a white ground we see two parallel lines. If we now open the other eye we see a third line between the other two lines. If the meridional adjustment of the eyes is perfect, all three lines will be parallel and horizontal; but if there is a tendency to deviation of the meridians from the proper adjustment the third line will be obliquely inclined to the other two lines.

We may also use the *Maddox rod* for finding the equilibrium

of the meridians. For this purpose we place a rod vertically before each eye (Fig. 131). The two lines of light as seen through the rods should form a continuous horizontal line. ***Any deviation of either line from the horizontal plane indicates cyclophoria,*** and the angle through which the rod must be turned in order to make the line appear horizontal measures the cyclophoria.

FIG. 132
Clinoscope (*Stevens*).

Another device available for measuring cyclophoria is the clinoscope of *Stevens* (Fig. 132). This is a contrivance for examining the lines known as *Volkman's disks* (Fig. 133). One line is seen with one eye, the other line with the other eye. The two lines are adjusted exactly in the vertical plane. If they appear to form a continuous line (Fig. 134) in the vertical plane there is no cyclophoria. ***If they appear as a broken line, there is cyclophoria*** or *cyclotropia,* and this is measured by turning the faulty

appearing line until it appears to be vertical. A scale which marks the degree through which the line is turned shows the amount of cyclophoria.

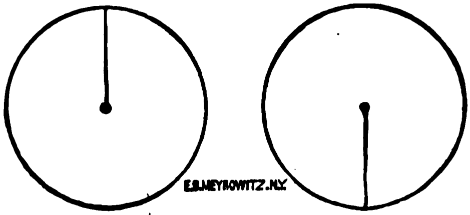

FIG. 133

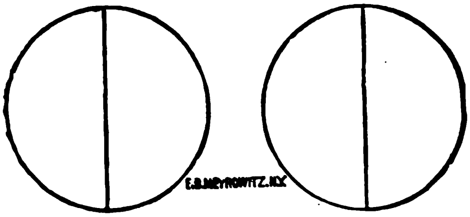

FIG. 134

The following authorities have been consulted in the preparation of the foregoing chapter:

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Howe. *Muscles of the Eye.*

Maddox. *Tests and Studies of the Ocular Muscles.*

Savage. *Ophthalmic Myology;* and *Ophthalmic Neuro-myology.*

Duane. *Extra-Ocular Muscles.* Posey and Spiller's *Eye and Nervous System.*

Worth. *Etiology and Treatment of Squint.*

Priestley Smith. *A Tape Measure for Strabismus.* Ophthal. Review, 1888.

Javal. *Manuel du Strabisme.*

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CHAPTER XVII

NON-PARALYTIC DISORDERS OF EQUILIBRIUM

Any deviation from perfect muscular adjustment constitutes *muscular imbalance.* Of the two general classes of muscular imbalance, *non-paralytic* and *paralytic,* we devote our attention in the present chapter to the former class.

Excess of Convergence

When from any cause the eyes tend to assume a degree of convergence greater than that required by the position of the point of fixation an abnormal tax is imposed upon the nervous system in order that the visual lines may be maintained in the proper directions for binocular vision. If the tendency to excessive convergence is considerable the great and continued strain results in nerve exhaustion, and beyond a certain period the effort for binocular vision cannot be maintained. The latent condition of *esophoria* then gives place to manifest error, *esotropia,* or *convergent strabismus,* and vision is performed with one eye, while the other deviates inward.

Latent excess of convergence may, therefore, be converted into *manifest strabismus* at certain times as when the eyes are tired from prolonged use, and especially in near vision, when spasm of convergence is frequently incited through the association of accommodation. In such cases the strabismus is *intermittent.*

But when the effort necessary for binocular vision is very great or when the fusion-impulse is weak, it usually happens that the child (*for convergent strabismus almost always develops in childhood*), having once learned the art of squinting with monocular vision, will altogether abandon the effort to maintain proper convergence. The strabismus thus becomes *constant* or *permanent.*

If the vision is equally good in the two eyes, either eye may be used for fixation while the other squints (*alternating strabismus*). But, as a rule, in strabismus one eye will be preferred to the other, and fixation will be performed always with the better

eye, while the inferior eye falls into a state of permanent deviation. Although thus *apparently* confined to one eye, this kind of strabismus is not a monocular affection. The excessive convergence is effected by innervation of both internal recti; but in order that the visual line of the fixing eye may be properly directed, adduction of this eye is prevented by suitable innervation of its external rectus, just as when convergence is maintained together with a lateral deviation of the two eyes (*Landolt*). In strabismus this is usually effected by turning the head to one side.

Although the convergence is always in excess of the appropriate amount, it diminishes or increases with the recession or approach of the object of fixation; moreover, the convergence-excess remains undisturbed throughout the field of fixation, for the two eyes move together in all directions. In this respect non-paralytic differs from paralytic strabismus, and it is because of this freedom of movement that the former is called *concomitant* strabismus.

In recently formed concomitant strabismus there is no abnormal limitation of the field of fixation in any direction, but when from long-continued overaction the internal recti have become permanently shortened while the external recti have become correspondingly weakened, the power of abduction (external rotation) falls appreciably below that of the normal eye; and since the internal rectus of the deviating eye is the muscle which undergoes the greater shortening, the external rotation of this eye is not infrequently less extensive than that of the other eye.

Etiology of Excessive Convergence.—We have learned that through the variation in the relative accommodation and convergence distinct binocular vision is possible in ametropia. The relation between accommodation and convergence may be so modified by long association that *orthophoria coexists with ametropia;* or the orthophoric condition may not be attained, but *whatever imbalance remains may be latent.* In hyperopia the tendency is towards excessive convergence, since the inordinately great accommodative effort required for distinctness of images provokes an abnormally great convergence impulse.

In childhood convergence is especially easy, owing to the smallness of the eyes and the shortness of the interocular distance. Because of this facility for convergence and of the irritation transmitted from the accommodation center, the internal recti are

thrown into a spasmodic condition in convergent strabismus, whereby the degree of strabismus is increased. This ***spasm of convergence*** gradually gives place to anatomical shortening of the internal recti muscles, and especially of the internal rectus of the deviating eye.

Spasm of convergence has also been attributed to a number of other causes (*corneal inflammations, etc.*), but for the most part without sufficient reason. It may, however, be due to ***hysteria*** or to other nervous hypersensitiveness.

The relative strength and the position of scleral attachment of the internal as compared with the external recti muscles must also be regarded as a factor in determining the predominance of convergence over divergence.

Defective development of the cerebral fusion centers is, doubtless, an important factor in the etiology of convergent strabismus. In certain cases of intractable alternate strabismus with normal visual acuity in each eye we may reasonably assume that there is a congenital absence of the fusion faculty, but in a much larger proportion of cases there are other factors to be considered which militate against the post-natal development of this innate faculty. The more important of these contributing causes have been mentioned in the chapter on *Hyperopia.*

Symptoms of Excessive Convergence.—Slight esophoria may give rise to no disturbance whatever. Higher degrees cause the group of symptoms which have been described as ***asthenopia.*** The least amount of esophoria which may produce asthenopic symptoms cannot be definitely stated, since this varies with the resisting power of the nervous system. In general, we may say that an amount not exceeding 3△ at six meters must be placed within the limits of normal equilibrium.

When the tendency to convergence is so great or the fusion impulse so weak that the proper directions of the visual lines cannot be maintained—that is, when esophoria passes into *esotropia* or convergent strabismus—muscular asthenopia is replaced by a new train of symptoms which originate from the loss of binocular single vision.

Deviation of the Non-fixing Eye.—The inward deviation of the cornea of the non-fixing eye is the ***characteristic objective*** symptom of convergent strabismus. This deviation

may be so slight as to be unnoticeable on casual observation, but usually it is apparent at a glance.

Diplopia.—In permanent non-paralytic convergent strabismus diplopia is not a common symptom because of the early age at which this kind of strabismus develops. Diplopia may be demonstrated in some cases of long continuance, but more frequently that part of the retina upon which the false image falls fails to transmit stimulation to the centers of consciousness. This loss of function results from the cultivated power of disregarding the false image. That part of the retina which has acquired this insensitiveness is called the *region of exclusion.*

In certain cases there appears to have developed a new association of nerve fibers whereby *the false image is fused with the true image,* the former being assigned its correct position in space. In these cases a temporary diplopia occurs after a successful operation for the strabismic defect.

Amblyopia Ex Anopsia.—The visual acuity of the deviating eye is much reduced in all long-standing cases of permanent non-paralytic convergent strabismus. In most of these cases the vision of the squinting eye was doubtless defective prior to the occurrence of strabismus, the defective vision being the determining cause of the strabismus; but abundant observation has shown that squinting eyes which possessed good visual power in early life have so far deteriorated after long-continued disuse as even to lose the power of fixation.

Notwithstanding the inferiority of vision of the squinting eye, this eye is still of material assistance in extending the field of vision. It is significant also that the extreme inner part of the retina, corresponding to the temporal field on the affected side, does not suffer the deterioration which involves the macular region.

Diagnosis of Excessive Convergence.—We make the diagnosis of excessive convergence by the application of the various equilibrium tests which were described in the preceding chapter. We distinguish between comitant and paralytic affections by noting whether the imbalance exists in all or only in certain directions of the gaze.

Treatment of Excessive Convergence.—The treatment of esophoria and convergent strabismus, in so far as this consists in the correction of any causative refractive error, has

been considered in previous chapters. When this correction, together with hygienic, tonic or other treatment indicated by the systemic condition, fails to afford relief, other methods must be adopted.

Prismatic Glasses.—A prism, *base out,* before each eye, may enable the eyes to retain binocular single vision, while the visual lines assume the excessive convergence which is evoked by the muscular balance. In this way diplopia and its alternative, excessive nervous strain to maintain proper convergence, may be avoided, and consequently subjective disturbance may be thus relieved. But this method has its limitations, for, on account of the distorting property of prisms, it is not possible to wear strong glasses of this kind. A strength of 4△ for each eye is the limit usually assigned.

In the application of this method it is usually advisable to correct only a portion of the esophoria, a prismatic strength of one-half or two-thirds of the amount manifested at six meters being, in favorable cases, sufficient to relieve the asthenopia.

Prisms prescribed for the relief of esophoric asthenopia must ordinarily be worn constantly.

In minor degrees of esophoria relief may be expected from the use of prismatic glasses; but, unfortunately, in many cases the excess of convergence is so great that only a small portion can be corrected within the limits prescribed for such glasses. In some cases, also, in which relief is at first afforded, the esophoria apparently increases under the relaxing influence of the prisms, so that the strength of the latter has to be increased. If the limit has already been reached, this method is no longer applicable.*

It is apparent that decentering a *convex lens* inward or a concave lens outward, has the effect of adding a prism, *base in,* to the lens; while decentering a *convex lens* outward or a *concave lens* inward has the effect of adding a prism, *base out.*

In a lens of 1 D a ray parallel to the axis and passing through the lens at a distance of 1 *cm* from the center, is deviated 1 *cm* in reaching the focus of the lens, 1 meter distant; that is, for this ray the lens has the same effect as a prism of 1△. If the lens has a power of 2 D the prismatic effect at a distance of 1 *cm*

*This apparent increase in the esophoria is not due to any injurious effect of the prisms. On account of a spasmodic condition of the muscles, or an over excitation of the nerve centers, a portion of the esophoria is not at first revealed; but under the influence of the prisms the eyes gradually assume their position of equilibrium.

from its center is 2△, and so on. Therefore, the rule is that *decentering a spherical lens (or a cylinder at right angles to its axis)* produces a prismatic effect equal to *as many prism diopters as there are diopters in the lens.*

We may write an order for the decentering of a lens in accordance with the foregoing rule, or we may order the required lens plus (+) the required prism, leaving to the optician the choice between decentering and grinding the spherical curvature upon the face of the prism. But here, as in all cases, we should test the accuracy of the optician's work by examining the glasses after they have been made. We may determine the strength of a prism by neutralizing the displacement with a prism taken from the trial case, or we may note the displacement on a prism-diopter scale. In testing a sphero-prism we must be careful to measure the prismatic effect at the center of the lens.

When the principal plane of the prism is to be placed horizontally or vertically, the simple designation *base in, base out, base up,* or *base down* suffices to denote the desired position; but when the principal plane—or the base-apex line—is to be placed in an oblique meridian, we denote the direction of the principal plane by the angular marking on the trial frame.

We may, if we so desire, replace a single prism in an oblique meridian by two prisms at right angles to each other, one vertical and the other horizontal. We may thus place the vertically acting prism before one eye and the horizontally acting prism before the other eye.

Stereoscopic Exercises.—In convergent strabismus in children if the deviation is not promptly overcome by the correction of the ametropia we should attempt to incite the impulse for binocular vision by stereoscopic exercises. The importance of this procedure was first shown by *Javal.*

Various special forms of stereoscopes and of pictures have been devised for the cultivation of binocular vision. Of these, *Worth's amblyoscope* is perhaps the most convenient, in that with it binocular vision is possible even when the eyes are affected with a high degree of strabismus. This instrument is also well adapted for changing the intensity of illumination on one side without affecting that of the other side, so that by means of small electric lamps the child's attention may be attracted to

the image in the amblyopic eye by making the illumination more intense for this eye than for the better eye.

In those cases in which it is not to be expected that stereoscopic training will overcome the strabismus, the prolonged daily use of such exercises with the amblyoscope is yet of very great value in preventing amblyopia ex anopsia and in developing the fusion sense while awaiting a suitable time for operative measures. The same exercises are likewise useful for developing the fusion sense and inciting binocular vision after operative measures have overcome the greater part of the strabismus.

Worth concludes, as the result of the examination of a large number of children, *that binocular vision is first attempted about the sixth month of age,* and that *the development of the fusion faculty is completed by the end of the sixth year.*

This constitutes the chief obstacle to this plan of treatment, since the very young children for whom it is applicable frequently fail to give the co-operation necessary for success. The experience of Worth, however, shows that much can be accomplished by the exercise of patience and care.

Bar reading consists in making use of a device which requires the use of both eyes in reading, as when we hold a pencil between the eyes and the printed page. This plan gives a simple means of exercising the amblyopic eye, but unfortunately it is not applicable until after the passing of the age which offers the greatest encouragement for the institution of binocular vision.

Use of Atropin and Bandaging in Developing the Amblyopic Eye.—In those cases in which stereoscopic exercises are not available, the amblyopic eye may be trained by bandaging the better eye for a brief period once or twice a day, so that fixation with the amblyopic eye is necessitated. The use of atropin in the better eye is also of material assistance, since it compels the inferior eye to be used for near vision.

Prism Exercises.—Exercising the diverging power consists in having the patient look at a distant point, as a candle flame, *alternately with and without divergence-prisms* (*bases in*), these being preferably placed in a spectacle frame and raised and lowered at intervals of five seconds (*Savage*). Those who advocate this method believe that the rhythmical contractions thus produced in the external recti strengthen these muscles or train the nerve centers presiding over divergence so as to enable them to over-

come the excessive convergence. Opinions differ as to the merits of prism exercise. My own belief, based partly upon theoretical grounds and partly upon practical results, is that it is of no value.

Operative Treatment.—When all other measures fail to give relief either in esophoria or in esotropia, operative treatment should be undertaken.

The operative treatment of esophoria consists in a carefully guarded tenotomy of the internal rectus or an advancement of the external rectus. In either operation it is preferable to divide the effect between the two eyes in the higher degrees of esophoria. Of these two operations tenotomy is more frequently selected as being the simpler and less painful at the time of operation and during the healing process. The possibility, however, of a resulting deficiency of convergence, as sometimes occurs, leads many surgeons to believe it more rational to strengthen the weak external recti, by advancement, than to weaken the power of the internal recti.

The surgeon may be aided in his choice of an operation by examination of the fields of fixation and of the power of convergence and divergence. *When the esophoria is due to weakness of divergence,* and not to overaction of convergence—that is, when convergence is not decidedly greater than the normal amplitude—advancement is the only permissible operation.

The operative treatment of convergent strabismus likewise consists in tenotomy of the internal rectus or advancement of the external rectus, the effect being preferably divided between the two eyes except in the lower grades of strabismus. When the operation is to be performed upon only one eye at the first sitting, the inferior (squinting) eye should always be selected.

It is especially in the extensive tenotomies undertaken for the cure of high convergent strabismus that subsequent deformity is liable to occur, such as *sinking of the caruncle, proptosis,* and *even extreme divergence with marked limitation of movement.* Hence, for the correction of those cases of convergent strabismus in which it is apparent that a moderate tenotomy on each eye will not suffice, an advancement of the external rectus combined with the tenotomy must be undertaken, the effect being preferably divided between the two eyes.

The proper age for operative intervention in convergent strabismus depends upon the probability of obtaining binocular vision. If the operation is to be undertaken solely for the cosmetic result,

vision being hopelessly defective in the squinting eye, the procedure should be delayed until the tenth, or twelfth year, or even later, since in a small proportion of cases a spontaneous cure of spasmodic convergence occurs in childhood. If, on the other hand, stereoscopic training with the amblyoscope evokes a strong desire for binocular fusion, an early operation is demanded (*Worth*), provided the non-operative methods aforementioned have proved unsuccessful.

For a description of the technique of tenotomy and advancement operations the reader is referred to works dealing with ophthalmic surgery.

Deficiency of Convergence

Deficiency of convergence is either *latent* or *manifest,* constituting, respectively, *exophoria,* and *extropia* or *divergent strabismus.*

As in excess of convergence, so in deficiency binocular vision may give place to strabismus with monocular vision only at certain times, as when the eyes are exhausted from prolonged use (*intermittent divergent strabismus*). If vision is equally good in the two eyes, either eye may be used for fixation while the other squints (*alternate divergent strabismus*); but if, as is usually the case, the vision of one eye is inferior to that of the other, the strabismus will be permanently confined to the inferior eye (*permanent divergent strabismus*).

As in convergent strabismus, so in non-paralytic divergent strabismus the conjugate movements are preserved throughout the field of fixation (*concomitant divergent strabismus*).

Etiology of Convergence Deficiency.—Myopia as a factor in the production of exophoria and divergent strabismus has been considered in Chapter XII. Myopia bears the same relation to deficiency as hyperopia does to excess of convergence: the weakness of the accommodative impulse, the elongation of the eyeballs, and the proximity of the farthest point of distinct vision, all aid in rendering convergence difficult.

Aside from the myopic condition. non-paralytic deficiency of convergence may arise from *overstrain* of the eyes in near work, from *innate preponderance of the external* over the internal

recti, from *reduced physical vigor,* and from *mechanical impediment* (as in exophthalmos).

Determining Causes of Divergent Strabismus.—The development of divergent strabismus from exophoria is favored by loss or deterioration of vision of one eye, and by so high a degree of myopia that the convergence required for binocular vision is difficult or impossible.

Divergent strabismus is ordinarily a condition of adult life; more rarely it develops in childhood, as in congenital myopia, or in high-grade hyperopia.

Symptoms of Convergence Deficiency.—Insufficiency of convergence gives rise to *muscular asthenopia,* especially when the eyes are tired from prolonged near work. The latter is sometimes impossible, so great is the disturbance produced by it. This disturbance is partly a symptom of overtaxation of the convergence function; but in the worst cases confused vision (*crossed diplopia*) from the impossibility of maintaining convergence is the chief factor.

The reasons assigned for the absence of diplopia in convergent strabismus are not applicable to divergent strabismus, since this develops in adult life; but diplopia is not a common symptom in the latter condition either, because divergent strabismus usually develops only when the visual acuity of one eye is much reduced, so that exclusion of the false image is quickly learned. In those cases in which both eyes possess good visual acuity diplopia is a troublesome symptom in the developmental stage, but it subsequently disappears or ceases to give annoyance. The power of excluding the false image is aided by the position of extreme divergence, which is on this account frequently induced, for when the image falls upon the periphery of the retina, it does not excite attention so readily as when it falls near the macula.

Diagnosis of Convergence Deficiency.—We make the diagnosis of convergence deficiency and the distinction between comitant and paralytic imbalance by the application of the tests which have already been described.

The existence of exophoria, as thus determined, at six meters is strong evidence that the converging power is abnormally weak; but the converse does not follow, for insufficient convergence for near work is not incompatible with orthophoria, or even esophoria, in distant vision. The determining test consists in the direct

measurement of the amplitude of convergence with the *ophthalmo-dynamometer*. The amplitude required depends upon the kind of work pursued, but an amount less than 8 *ma*, which corresponds to a near-point of five inches, is insufficient for continuous reading or writing, since only about one-third of this amplitude is available for prolonged use.

It is in this condition also, as in excessive convergence, important, especially in regard to operative treatment, that we measure the diverging power by means of prisms.

In strabismus the angle of deviation and the field of fixation should be measured as described in the preceding chapter.

Treatment of Convergence Deficiency.—The importance of correcting any causative refractive error is apparent, and has been sufficiently considered in previous chapters. In addition, avoidance of overuse of the eyes in near work and other hygienic measures must be inculcated, according to the necessities of the case.

Prismatic glasses (bases in) are useful, within the limitations to which such glasses are restricted, for the relief of exophoric asthenopia. In those cases in which asthenopia arises only after prolonged near work, the glasses may be worn for such work only; but when there is marked exophoria at six meters, relief is usually afforded only by the constant use of the glasses.

As in excess of convergence, so in deficiency we often find that prisms which for a time relieve the asthenopic symptoms seem to increase the heterophoria. In such cases if the limit to which prismatic glasses are subject has been reached, operative treatment may be required.

Prism Exercises.—Those who advocate prism exercise in the treatment of excess recommend it also, with greater confidence, in deficiency of convergence. The method of application is similar to that used in excess of convergence, except that the bases of the prisms are reversed, being placed towards the temples.

Stereoscopic Training.—Owing to the circumstances under which divergent strabismus usually develops, training with the stereoscope is less frequently indicated than in convergent strabismus. Occasionally, however, *when the impulse for binocular vision is feeble,* while the visual acuity in each eye is good, stereoscopic exercises, either alone or in conjunction with surgical treatment, may prove useful.

Operative Treatment.—For the relief of asthenopia operative procedure should be undertaken only after all other measures have proved unsuccessful. Of the two operations—tenotomy of the external and advancement of the internal rectus—tenotomy is the simpler, and may be selected in appropriate cases. There is less danger of a disastrous result from a properly perfomed tenotomy of the external than of the internal rectus. Tenotomy should not be selected, however, unless the prism test shows the divergence to be decidedly in excess of the normal amount.

In strabismus of long standing simple tenotomy has but little effect in overcoming divergence. For the correction of such cases advancement (usually on both eyes) should be performed.

Vertical Imbalance

In convergent strabismus of high degree there is usually superadded an upward deviation of the squinting eye, while divergent strabismus is usually complicated with downward deviation. Aside from such cases *non-paralytic vertical strabismus is* not common. *Hypertropia,* though usually considered with comitant errors, is probably almost always of paralytic origin.

Concomitant hyperphoria is, on the other hand, quite common. It is usually of low degree, 1△ or 2△.

Etiology.—The explanation usually given for the occurrence of hyperphoria is that the balance of power between the elevator and the depressor muscles of one eye differs slightly from that of the other. *Stevens* regards *declination* of the retinal meridians as the primary error.

Symptoms and Diagnosis.—Vertical imbalance may cause asthenopia, diplopia, monocular vision, or torticollis from compensatory obliquity of the head. We make the diagnosis of hyperphoria by the application of one or more of the equilibrium tests already described. We may also with advantage measure the power of right and left *sursumduction;* that is, the power of the right and left eye, respectively, to deviate relatively upward. The strongest prism, *base down,* before the right eye or *base up* before the left eye, with which diplopia can be overcome, measures ***right sursumduction.*** Similarly, the strongest prism, *base down,* before the left eye or *base up* before the right eye, with which diplopia can

be overcome, measures the *left sursumduction.* In normal balance sursumduction, right or left, is about 2△ (*Stevens*).

A higher degree of sursumduction for one eye than for the other indicates hyperphoria of the eye which has the greater sursumduction. In order to determine whether the relative hyperphoria is due to overaction of the elevator muscles of the higher eye or to underaction of the depressors of the lower eye, recourse must be had to measurement of the fields of fixation.

Uncomplicated vertical strabismus is determined by the tests which reveal hyperphoria, and in addition there is vertical diplopia without the aid of the horizontal prism.

Treatment.—Since hyperphoria does not reach a high degree of deviation, the asthenopia to which this imbalance gives rise may in favorable cases be overcome by the use of prismatic glasses. The strength of the glass should ordinarily be divided between the two eyes, the base being placed down before the higher eye and *vice versa*. The same proportion of error (one-half or two-thirds) should be corrected as has been recommended for other forms of heterophoria.

The concurrence of slight hyperphoria with greater lateral heterophoria does not indicate the necessity of correcting the vertical error; at least, until correction of the lateral imbalance has failed to give relief. On the other hand, as shown by *Stevens*, the hyperphoria is in some cases the primary defect, the lateral disturbance being produced by the muscular effort to overcome the vertical error. When it becomes necessary to correct both lateral and vertical heterophoria the equivalent prism and the position of its base can be determined in accordance with instructions given in Part I (p. 30); or the prism before one eye may be used to correct the vertical error while that before the other eye corrects the horizontal error.

If prismatic treatment proves unsuccessful in hyperphoria or in vertical strabismus, *tenotomy* of the superior rectus of the higher eye or *advancement* of the inferior rectus is permissible, provided the symptoms are of sufficient gravity to justify operative interference. But here, as in other forms of heterophoria, we must bear in mind that the existence of slight or even considerable deviation from orthophoria is by no means positive evidence that this deviation is the cause of headache or other

reflex disturbance. If prisms do not afford a fair measure of relief in heterophoria, except in the highest degree of lateral insufficiency, it may reasonably be assumed that operative treatment will be equally unsuccessful.

Cyclophoria and Cyclotropia

The terms *cyclophoria* and *cyclotropia* (or *declination*) have already been described, and the methods of detecting such anomalies have been given.

Cyclophoria, being a latent condition, coexists with binocular vision, and may therefore give rise to asthenopia.

Cyclotropia, being a manifest imbalance, occurs in certain forms of strabismus.

Very great importance is attached to these conditions by *Stevens* and by *Savage,* who have devoted much study to the elucidation of this very difficult subject. While the mal-adjustment of the retinal meridians is doubtless capable of causing much physical disturbance in those cases in which the imbalance is considerable, my experience has not led me to believe that cyclophoria is a common contributing element in the etiology of asthenopic symptoms.

Treatment.—*Savage* recommends exercising the oblique muscles with cylindrical lenses. *Stevens* advises operative treatment. This consists in changing the position of attachment of the upper or lower part of an internal or external rectus, so as to secure the proper rotation of the eye on its antero-posterior axis.

Anophoria, Anotropia; Katophoria, Katotropia

These rare conditions have also been described as *double vertical strabismus. In anotropia,* when either eye performs fixation, the other eye deviates upward; *in katotropia,* when either performs fixation, the other eye deviates downward.

In anotropia the head is bent forward, and *in katotropia* it is bent backward, so as to counteract the effect of the deficient ocular rotation.

Prisms, base down, before each eye, in upward tendency and base up before each eye in downward tendency may be of use. *Stevens,* who regards the primary trouble as an error of declination, recommends operative treatment.

Spasmodic Conjugate Deviation

Spasmodic conjugate deviation sometimes occurs as a symptom of irritative cerebral lesion, being the condition opposite to paralytic conjugate deviation.

Nystagmus

Nystagmus consists in a rapid, short, oscillatory motion of the eyes. The direction of motion may be lateral (*horizontal nystagmus*), vertical (*vertical nystagmus*), or there may be a rotary motion around the antero-posterior axis (*rotatory nystagmus*). The last variety may be combined with horizontal or vertical motion (*mixed nystagmus*). Both eyes are affected, except in rare instances. The nystagmus is more pronounced in some positions than in others, being worse in forced positions of the eyes.

Etiology.—Nystagmus is very common among coal miners, being due to the long-continued use of the eyes in forced rotation obliquely upward (*miners' nystagmus*).

This affection also occasionally develops in adult life as the result of cerebral lesion (*disseminated sclerosis*).

Aside from the aforementioned conditions, nystagmus almost always dates from early infancy. It occurs when the vision of both eyes is so highly defective that the impulse for macular fixation is not acquired. It does not occur in complete blindness; hence, it is apparent that the nystagmic movements are in some way associated with the effort to obtain better vision, the improvement of vision being derived from these movements in the same way, perhaps, that the peripheral field of vision is greater when the examiner moves the test object to and fro than when this object is held motionless.

Chief among the causes of such defective vision as results in nystagmus are the complications of *ophthalmia neonatorum*, *albinism*, *congenital opacity* of the cornea or lens, and sometimes, *very great refractive error*.

Very rarely congenital nystagmus has been found to coexist with good visual acuity; in such cases the movements must be attributed to *some anomaly of the nerve centers*.

Symptoms and Diagnosis.—In nystagmus which arises in infancy there are no subjective symptoms attributable to the oscillatory movements, but in that which develops in adult life the

motion of the eyes makes all objects appear unsteady, with resulting *confusion of vision, vertigo,* and other disturbances.

The diagnosis of nystagmus is readily made from visual inspection. Clonic contractions of the ocular muscles occur physiologically when the attempt is made to hold the eyes in the position of maximum rotation. This condition should not be mistaken for nystagmus, which is present in all directions of the gaze.

Treatment.—Miners' nystagmus is cured by cessation from coal-digging. If possible a permanent change of occupation should be made, since the disease is liable to return on renewal of work in the mines.

Treatment is evidently unavailing in nystagmus which results from incurable lesion of the brain or of the eyes. Even in those cases in which vision can be improved by iridectomy or other surgical procedure, the nystagmus is benefited only when the operation is performed at an early age.

Disorders of Motility Caused by Mechanical Impediment

Limitation of ocular movement may be due to *exophthalmos, orbital tumor,* or allied condition. Such cases require no special consideration here, the disturbance of motility being of secondary importance in comparison with the etiological condition.

Loss of function is also produced by *improperly performed tenotomy* or by *accidental section of a muscle back of Tenon's* capsule.

The following authorities have been consulted in the preparation of the foregoing chapter:

Stevens, *Motor Apparatus of the Eyes.*

Maddox, *The Ocular Muscles.*

Howe, *The Muscles of the Eyes.*

Duane, *Extra-Ocular Muscles,* Posey and Spiller's *Eye and Nervous System.*

Landolt, *Anomalies of the Motor Apparatus of the Eyes,* Norris and Oliver's *System of Diseases of the Eye.*

Worth, *Etiology and Treatment of Squint.*

Javal, *Manuel du Strabisme.*

Savage, *Ophthalmic Myology, and Ophthalmic Neuro-Myology.*

Fuchs, *Text Book of Ophthalmology.*

Donders, *Anomalies of Refraction and Accommodation.*

Prentice, *Metric System of Numbering and Measuring Prisms,* Arch. of Ophthal., 1890.

CHAPTER XVIII

PARALYTIC DISORDERS OF MOTILITY

Paralytic disturbance of function may be due to lesion in any part of the course of the motor nerves, from their peripheral expansions to the highest centers presiding over muscular action. As regards the motor apparatus of the eyes such disorders may be conveniently divided into two classes. The first class includes paralysis arising from a lesion situated anywhere in the course of the nerve from its peripheral expansion up to and including the nucleus which controls monocular muscular action. The second class embraces those rarer cases of paralysis of associated movement, due to lesion of the centers which preside over the working of the two eyes in unison, or to lesion of the higher centers or of the fibers which convey impulses from these centers to the motor centers.

Paralyses of the Ocular Muscles

In the first class of paralytic disorders, the loss of muscular power is absolute; that is, it exists equally for all innervational impulses. The loss of power may be partial (*paresis*) or total (*complete paralysis*).

Paralysis may affect any one of the ocular muscles singly, or it may involve a group of muscles of one eye, or one or more of the muscles of each eye.

The external rectus and the superior oblique are most frequently singly paralyzed, since each of these muscles has its independent nerve; while the internal, the superior, and the inferior recti, and the inferior oblique, all being .supplied by the third nerve, are usually involved in a combined paralysis. Bnt sometimes these muscles also are singly paralyzed.

All the extrinsic muscles of the eye may be paralyzed, while the iris and ciliary muscle are unaffected, since the nucleus of these intrinsic muscles is anterior to that of the extrinsic muscles. Paralysis of this kind is called *external ophthalmoplegia* in contradistinction to *internal ophthalmoplegia,* which affects only the

iritic and ciliary muscles. Paralysis of both interior and exterior muscles constitutes *total ophthalmoplegia.*

Congenital paralysis may affect all the muscles of the eye, but it is usually confined to one external rectus, or to the two superior recti in conjunction with ptosis. In these cases the paralysis is associated with failure of muscular development, but the origin of the disease is probably nuclear.

A peculiar and rare form of congenital paralysis consists in a loss of the power of abduction, associated with retraction of the eyeball and narrowing of the palpebral fissure in adduction.

Ophthalmoplegic migraine (*Charcot*) is a form of recurrent paralysis attended by nausea, and headache on the affected side. The disease attacks children and young adults. At the early stage of the disease the muscles regain their power in the interval between the attacks, which may last from a few days to several months, but later a permanent paresis results. The pathology of this affection is obscure. The third nerve is the usual seat of this kind of paralysis, but a few cases have been observed in which the sixth nerve was attacked.

Etiology.—Oculo-muscular paralysis may be due either to intra-cranial or to orbital lesion. *Intra-cranial paralysis* may be again divided, in accordance with the site of the lesion, into *nuclear, fascicular,* and *basilar.* The most common cause of intra-cranial paralysis is *syphilis,* the gummatous deposit of which produces pressure upon the nerves or their nuclei. The principal other causes are brain tumor, meningitis, aneurism, hemorrhage, tabes (usually regarded as a late manifestation of syphilis), disseminated sclerosis, and certain diseases which are especially liable to cause injury to nerve tissue, as diabetes and poisoning by alcohol, tobacco, and lead.

Orbital paralysis may result from diphtheria, rheumatism, diabetes, or lead poisoning, from orbital tumor, hemorrhage, fracture or exostosis in the region of the optic foramen, sinusitis, etc.

General Symptoms.—There are six important general symptoms of oculo-muscular paralysis: limitation of movement, strabismus, diplopia, false projection, vertigo and unsteadiness of gait, and oblique position of the head. These general symptoms are common to all paralyses.

Limitation of Movement.—The rotative power of the eye is always abnormally circumscribed in the field of action of

the paralyzed muscle. In complete paralysis this limitation is readily determined by directing the patient to follow with his eyes (his head being unmoved) the point of a pencil or other object moved in various directions before the eyes, when the examiner will notice that the paralyzed eye fails to follow the other in certain movements. In incomplete paralysis (paresis) the limitation of movement is often too slight to be thus determined. This is especially the case in affection of the oblique muscles. In such cases assistance may be gained from the measurement of the field of fixation with the perimeter or with the tropometer.

Paralytic Strabismus.—This differs from concomitant strabismus in that the latter is maintained in all directions of the gaze, while the former is manifested only when the object of vision lies within the field of action of the paralyzed muscle. Thus, in paralysis of the left external rectus the right eye will properly fix an object situated on the left side, but the left eye cannot be turned in this direction; consequently there will result a convergent strabismus of the left eye. When, however, the gaze is directed straight forward the strabismus becomes less marked, or in paresis it may vanish, giving place to binocular fixation, as it will also do in complete paralysis when the object is moved to the extreme right.

Between paralytic and concomitant strabismus there is also another point of difference which is of diagnostic importance: in concomitant strabismus the angular deviation of the non-fixing eye is the same, whether one or the other eye is used for fixation; but in paralytic strabismus the deviation of the paralyzed eye (*primary deviation*) when the sound eye is fixing is less than the deviation of the sound eye (*secondary deviation*) when the paralyzed eye performs fixation.

The explanation of the greater secondary than primary deviation in paralysis is to be found in the binocular innervation of the associated muscles involved in fixation. Owing to the diminution of power of the paralyzed muscle, a very strong impulse is required to enable the affected eye to move into the fixation position—as great an impulse as would be required in a state of health to effect extreme rotation. This strong impulse is equally conveyed to the associated sound muscles of the other eye, and a proportionately strong contraction results.

Diplopia.—This is the most prominent subjective symptom

of paralysis developing in the muscle of an eye whose visual acuity is good. The diplopia occurs coincidently with the strabismus; that is, it is manifested whenever the gaze is directed towards the field of action of the paralyzed muscle. The patient may himself be aware of the existence of diplopia, or he may complain only of confused vision.

The analysis of diplopia is of the greatest diagnostic importance, for it is from the relative position of the true and the false image and from the direction of the gaze in which diplopia occurs that the seat of paralysis is most readily determined in those cases in which the limitation of movement is too slight to be apparent.

False Projection.—We have learned in the study of concomitant strabismus that the false image is improperly projected, so that homonymous or crossed diplopia results according as the strabismus is convergent or divergent. The same error is made in paralytic strabismus; but in addition there is another kind of false projection which occurs when the paralyzed eye is performing fixation, the sound eye being covered. This false projection is due to the *muscular sense,* which enters largely into the judgment as to the position of an object relatively to the body. We know that a strong impulse is required in order to perform fixation of an object situated to the extreme right (for instance). If the right external rectus is paralyzed, it will require just as great an impulse for the right eye to fix an object situated slightly to the right as would be required to effect extreme rotation to the right in a healthy eye. Hence, if the subject of such paralysis, having his sound eye covered, is asked to look at an object situated on his right and then to point quickly with his finger towards the object, he will point too far to the right, because of the great innervation necessary to produce the requisite action of the paralyzed external rectus. But in a moment, when he sees his finger pointing in the wrong direction, he will rectify his error. This is called *Graefe's touch test.*

Vertigo and Unsteadiness of Gait.—These disturbances are the direct result of the diplopia and false projection. They disappear upon closure of the paralyzed eye.

Oblique Position of the Head.—This characteristic symptom results from the endeavor to avoid diplopia by turning the head

towards the field of action of the paralyzed muscle. The rotation of the head thus supplants that of the eyes.

Symptoms in Old Paralysis.—The foregoing symptoms become less characteristic the longer the paralysis has existed. The strabismus usually increases from contraction of the antagonistic muscles, and thus, existing to some extent throughout the field of fixation, it simulates concomitant strabismus. Diplopia ceases to give annoyance or it even disappears entirely if the habit of exclusion is acquired. False projection also disappears, since it is learned that an exaggerated impulse corresponds to only a moderate movement. With the disappearance of diplopia and false projection vertigo also vanishes.

Paralysis of the External Rectus (Sixth Nerve).—The *special symptoms* which characterize this paralysis are inability to rotate the eye outward (abduction), convergent strabismus, homonymous diplopia (Fig. 135), and rotation of the head towards the paralyzed side, and false projection towards this side. These symptoms are most pronounced when the object of vision lies on the side corresponding to the affected side, and they vanish when the object is moved to the extreme opposite side.

Paralysis of the Internal Rectus.—The characteristics of this paralysis are limitation of internal rotation (adduction), divergent strabismus, crossed diplopia (Fig. 136), turning of the head towards the sound side, and false projection towards this side. The symptoms are most pronounced when the object of vision lies on the side corresponding to the sound eye, and they vanish when the object is moved to the extreme opposite side.

Paralysis of the Superior Rectus.—The external and internal recti rotate the eyeball around a single (vertical) axis when the object of vision is on a level with the eyes, and consequently the resulting homonymous or crossed diplopia is simple; that is, the two images are on the same level and parallel. But the action of all the other ocular muscles is more complex, as referred to the three primary axes, and paralysis of these muscles is attended by a more complicated relation between the true and false image than follows paralysis of the external or internal rectus.

The superior rectus turns the eye directly upward only when the eye is simultaneously abducted to such a degree that the

antero-posterior diameter lies in a straight line with the line of action of the muscle. When the gaze is directed straight for-

Paralysis of left eye.

FIG. 135

Paralysis of External Rectus

Lateral separation of images increases in looking towards the paralyzed side.

Paralysis of right eye.

Paralysis of left eye.

FIG. 136

Paralysis of Internal Rectus

Lateral separation of images increases in looking towards the sound side.

Paralysis of right eye.

Paralysis of left eye.

FIG. 137

Paralysis of Superior Rectus

Vertical separation increases in elevation and abduction. Lateral separation diminishes in abduction. Obliquity increases in adduction.

Paralysis of right eye.

Paralysis of left eye.

FIG. 138

Paralysis of Inferior Rectus

Vertical separation increases in depression and abduction. Lateral separation diminishes in abduction. Obliquity increases in adduction.

Paralysis of right eye.

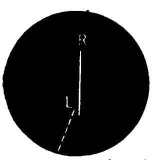
Paralysis of left eye.

FIG. 139

Paralysis of Inferior Oblique

Vertical separation increases in elevation and adduction. Lateral separation diminishes in adduction. Obliquity increases in abduction.

Paralysis of right eye.



Paralysis of left eye.

FIG. 140

Paralysis of Superior Oblique

Vertical separation increases in depression and adduction. Lateral separation diminishes in adduction. Obliquity increases in abduction.

Paralysis of right eye.

ward, the action of the muscle is divided between elevation, adduction, and rotation of the cornea about the antero-posterior axis, and the last-named action increases at the expense of the others as the adduction is increased. Hence, it is only in the first-mentioned position that paralysis of the superior rectus is accompanied by simple vertical diplopia; in other directions of the gaze the false image is displaced both vertically and laterally, and is obliquely inclined to the true image because of the rotation of the meridians of the eye.

In paralysis the displacement of the false image always corresponds to the direction of normal action of the paralyzed muscle, for the paralysis is followed by a turning of the eyeball opposite to that of the normal muscular action, and we know that the false image is displaced in a direction opposite to the turning of the eye.

Since the superior rectus turns the eye upward and inward and rotates the upper end of the vertical meridian inward, the false image must occupy the position represented in Fig. 137; that is, the diplopia is crossed, and the false image is above the true image, the lower extremity of the former being inclined towards the latter. The lateral separation of the images diminishes in abduction, the obliquity is least in abduction and greatest in adduction, and the vertical separation is greatest in looking upward.

The other symptoms, limitation of movement upward and inward, downward strabismus, and false projection require no special mention. The head is usually inclined backward and towards the shoulder of the healthy side.

Paralysis of the Inferior Rectus.—What has been said of the superior rectus applies equally to the inferior rectus, with the modification that the inferior rectus draws the eye downward and inward and rotates the upper end of the vertical meridian outward; hence, in looking forward and downward there is slightly crossed diplopia, the false image being below the true image, and having its upper end inclined towards the true image (Fig. 138). The vertical separation diminishes on looking upward, the lateral separation diminishes in abduction, and the obliquity is least in abduction and greatest in adduction.

The limitation of movement is downward and inward, the strabismus upward and outward, and the inclination of the head downward and towards the shoulder of the paralyzed side.

Paralysis of the Inferior Oblique.—The inferior oblique turns the eye upward and outward and inclines the upper end of the vertical meridian outward; hence, the false image is displaced upward and outward (that is, homonymously), and its upper extremity is inclined away from the true image (Fig. 139). The vertical separation of the images increases when the patient looks upward and towards the sound side (adduction); the obliquity increases when he looks towards the paralyzed side (abduction); the lateral separation diminishes in adduction.

The limitation of movement is upward and outward, the strabismus is slightly downward and inward, and the rotation of the head upward and towards the paralyzed side, and inclined to the shoulder of this side.

Paralysis of the Superior Oblique.—The superior oblique turns the eye downward and outward and rotates the upper end of the vertical meridian inward; hence, the false image is displaced downward and outward (homonymously), and its upper extremity is inclined towards the true image (Fig. 140). The vertical separation of images increases in looking downward and towards the sound side (adduction); the obliquity increases in looking towards the paralyzed side (abduction); the lateral separation diminishes in adduction.

There is slight limitation of movement downward and outward, with a corresponding strabismus upward and inward. The rotation of the face is downward and towards the paralyzed side, with the head inclined towards the shoulder of the sound side.

Paralysis of the Third Nerve.—Paralysis, either complete or partial, of all the muscles supplied by the third or oculomotor nerve is more common than paralysis limited to one of these muscles. In complete paralysis the appearance is unmistakable: the eye, being subjected to the unopposed action of the external rectus and the superior oblique, is deviated outward and downward, the upper lid droops over the eye (ptosis), there is mydriasis and cycloplegia (if the intrinsic muscles are involved), and not infrequently proptosis is present, because of the relaxation of the recti muscles, which normally draw the eyeball into the orbit.

Since the eye is drawn outward and slightly downward, having the upper end of its vertical meridian inclined inward, the false image must be displaced inward (crossed diplopia) and

upward, while its upper extremity is inclined towards the true image.

The effect of varying the direction of the gaze requires no special consideration, in view of what has already been said in regard to paralysis of the individual muscles. The head is turned towards the sound side, and is inclined towards the shoulder of the paralyzed side; the head is also thrown back in order to supplant the deficient downward rotation, and to compensate for the inability to raise the upper lid.

In incomplete paralysis ptosis may not be present, and the other symptoms (including the diplopia) are modified in accordance with the extent to which the various muscles are affected.

Combined Paralysis of the Ocular Muscles.—Several or all of the motor nerves of the eye may be simultaneously paralyzed, either from peripheral or nuclear lesion. Thus a nuclear paralysis of the third nerve is not infrequently associated with paresis of the fourth and sixth nerves, as is manifested by deficient action of the superior oblique and external rectus in conjunction with third nerve paralysis. By a further extension of the disease process the paresis of these two nerves may develop into complete paralysis, thus causing absolute immobility of the eyeball. Similarly, the adjoining nuclei of the nerves of the other eye may be attacked, with resulting paresis or paralysis of some or all of the muscles of this eye.

Diagnosis.—The existence of paralysis of an ocular muscle is suspected when a patient complains of confused vision, vertigo, and uncertainty of gait, and when in addition it is noticed that he does not direct his gaze straight forward, but turns his head towards one side, inclining it, perhaps, at the same time towards one shoulder. In such a case the suspected diagnosis is confirmed if direct inspection reveals limitation of movement and strabismus, the latter appearing or disappearing according as the gaze is directed towards or away from the field of action of the affected muscle.*

But in the more common condition of parésis of one or more of the muscles the limitation of movement cannot usually be determined by simple inspection. The appearance of slight

*Loss of movement due to section of a muscle may be excluded by the history of the case.

strabismus is also liable to be deceptive, for apparent strabismus is not infrequently coexistent with binocular single vision.

If the strabismus is only apparent, binocular fixation may be demonstrated by the cover test and by the other methods enumerated in Chapter XVI. If real strabismus is revealed by these tests, paralytic is distinguished from concomitant strabismus in accordance with the characteristics of each; but in the exact diagnosis of the degree and seat of paralysis the study of the field of fixation and of the diplopia are the two essential matters.

Measurement of the Field of Fixation.—This is useful not only for the assistance which it renders in making a diagnosis, but also for the record which it affords as to the degree of paralysis. It enables the physician to know whether the affection is improving under treatment. The field of fixation is determined with the tropometer or perimeter, as previously described.

Analysis of Diplopia.—The existence of diplopia is demonstrated by directing the patient to look at a candle-light or other suitable illumination, placed at a distance of three meters or more. The examination should be conducted in a darkened room, and preferably against a black background. If diplopia exists, two lights will be seen. The image which is well defined (provided the visual acuity of the non-paralyzed eye is good) and correctly projected is the true image, while the indistinct and incorrectly localized light is the false image. By covering first one and then the other eye we determine which eye furnishes each image; or we may place a red glass before one eye, thus coloring the light as seen with this eye.

After the existence of diplopia has been determined, the field of single vision and the field of diplopia are ascertained by moving the light in various directions, while the patient follows it with his eyes, his head remaining unmoved; or, as recommended by *Landolt,* the light may be stationary, while the patient's head is rotated in the various directions.

In making the diagnosis of the seat of paralysis the main points to be noted are: (1) Whether the false image is seen with the right or with the left eye; (2) whether the diplopia is homonymous or crossed; (3) whether the two images are parallel or obliquely inclined, and, if inclined, the relative direction of the false image; (4) whether the two images are on a level or one

higher than the other; in the latter case, whether the true or the false image is the higher; and (5) the effect of varying the direction of the gaze upon the lateral and vertical displacements and upon the obliquity.

By careful study of these features in connection with the study of the physiological action of the ocular muscles and of the result of their paralysis, as delineated in the foregoing diagrams, a proper diagnosis may usually be reached. Simple as this procedure may seem, the diagnosis of oculo-muscular paralysis is in many cases a very difficult task. This is because the test on which we must mainly rely (diplopia) is *subjective*, and even intelligent persons are very liable to error in describing these unfamiliar visual sensations. In the examination of ignorant or unobserving patients it is at times well-nigh impossible to gain intelligible answers. The most difficult cases are those of old paralysis and of paralysis complicated with defective visual acuity. In old paralysis and that in which the acuity of the paralyzed eye is defective, diplopia is with difficulty evoked and the direction of projection is uncertain. In paralysis complicated with defective acuity of the non-paralyzed eye it is hard to distinguish between the true and the false image.

Measurement of the Degree of Strabismus.—If the separation between the diplopic images is not too great, fusion may be effected by the interposition of a prism before one eye. When the prism is placed before the paralyzed eye the position of its base must correspond with the direction of displacement of the false image. When the prism is placed before the sound eye its base must be in the opposite direction. It is impossible to rectify the obliquity of the false image with a prism, but when the two images are otherwise brought together the obliquity is usually overcome either by rotation of the head or with the aid of the sound eye, so that complete fusion of the images results. The strength of the prism required for fusion measures the paralysis, each prism-diopter representing about one-half of a degree of strabismus. For the purpose of record the measurements should always be made with the object of vision in the same direction.

When the strabismus is too great for prismatic measurement, the perimeter may be used, just as in the measurement of concomitant strabismus.

Still another method consists in measuring, on an opposite

wall, the linear distance between the two images; the distance of the patient from this wall being known, the angle of strabismus may be deduced.

Determination of the Site of the Lesion Productive of Paralysis.—The site of a lesion which produces paralysis is to be conjectured partly from the apparent etiology and partly from the accompanying symptoms.

Thus paralysis resulting from rheumatism, diabetes, lead-poisoning, or diphtheria is usually peripheral (*orbital*), although all except the first of these diseases is known to be capable of producing also nuclear paralysis. *Orbital paralysis* may also be diagnosticated when there are definite symptoms pointing to orbital fracture, hemorrhage, inflammation, or tumor.

Similarly, in paralysis complicating meningitis a *basilar lesion* would be suspected. Basilar paralysis may also be caused by hemorrhage, tumor, or aneurism compressing the ocular nerves in this part of their course. A basilar lesion would be especially indicated by symptoms of involvement of the whole group of adjacent nerves of one side, including the olfactory, optic and the trigeminal, in addition to the motor nerves of the eyeball.

A fascicular lesion is determinable only in crossed paralysis, that is, when the paralysis affects the third or sixth nerve of one eye with simultaneous hemiplegia of the opposite side. The lesion (*hemorrhage or tumor*) must in this case lie in the pyramidal tract (or adjacent to it), so that it injures the nerve fibers after they have left their nucleus, and at the same time injures the fibers of the tract. Since the latter fibers cross to the opposite side below this point, the hemiplegia is on the side opposite to the affected eye. The lesion would be near the upper or lower border of the pons, according as the third or the sixth nerve were involved. The seventh (facial) nerve may be involved in conjunction with the sixth.

A *nuclear* lesion can be positively diagnosticated in paralysis of the third nerve without involvement of the internal branches. A peripheral lesion would not exclude the fibers which supply the intrinsic muscles, but owing to the fact that the nucleus for the latter fibers is anterior to the nucleus for the rest of the nerve, a nuclear lesion may not implicate the internal branch.

It does not follow, however, that involvement of both external and internal muscles is necessarily due to peripheral dis-

ease, for a morbid process affecting the gray matter on the floor of the fourth ventricle may evidently attack both nuclei of the third nerve. It may also attack the other nuclei, thus causing paralysis of all the muscles of the eye.

Treatment.—*Diphtheritic paralysis* usually undergoes a spontaneous cure, which, however, should be assisted by tonic and hygienic measures.

Rheumatic paralysis also affords, as a rule, a favorable prognosis. The treatment consists in regulation of the diet, and in the administration of anti-rheumatic remedies. This paralysis is liable to recurrence and sometimes proves incurable.

Diabetic paralysis is favorably influenced and sometimes cured by proper regulation of the diet. In *lead paralysis* a more healthful occupation should be sought, and absorptives (*iodides*) should be administered.

In orbital paralysis resulting from fracture, sinusitis, cellular inflammation, exostosis, tumor, or other affection, the prognosis varies in accordance with the extent of injury inflicted upon the nerve tissue. The treatment consists in removing the causal lesion, as far as this may be possible.

Paralysis which is due to the *various forms of poisoning* (by *alcohol, tobacco,* etc.) affords a favorable prognosis, provided the deleterious substance is eliminated and its further access prevented before destruction of the nerve tissue ensues.

Syphilitic paralysis is usually amenable to treatment if this is undertaken in good season; but occasionally this form of paralysis resists the most energetic treatment, destruction of tissue taking place before absorption of the pathological deposit can be effected.

Tabetic paralysis not infrequently disappears with the advance of the systemic disease; but, in general, paralyses resulting from incurable brain affections present an unfavorable prognosis, treatment being from the nature of the case unavailing.

In general the iodides constitute our mainstay in the treatment of ocular paralysis. Strychnin also is a favorite remedy, being administered usually as a routine procedure in those cases in which there is no apparent indication for the use of the iodides. Electricity, which was formerly much used in the treatment of ocular paralysis, probably has no beneficial action in this disease.

Even in the most favorable cases paralysis is essentially a

chronic affection; several weeks must elapse—more frequently two or more months—before a cure can be effected.

Prismatic Glasses.—In slight paresis, the separation of the images not being great, the diplopia may be avoided by the use of prisms. Although the degree of paralytic strabismus varies with the direction of the gaze, so that it is not possible to order a prism which will prove satisfactory throughout the field of fixation, yet much comfort is derived from a prism which relieves the diplopia in the most common position of the eyes—forward and slightly downward. In paresis of one of the depressor muscles, the superior oblique or the inferior rectus, it may suffice to annul the vertical displacement by a prism with its base down. Unless the prism is very weak its strength should be divided between the two eyes, the base of the prism before the sound eye being placed upward. If both vertical and lateral displacements must be corrected, the base of the prism must have an intermediate direction; or the vertical error may be corrected by one prism, its base being up or down, while the lateral error is overcome by the prism before the other eye, its base being in or out, as required.

It is not necessary to overcome the entire strabismus by the prismatic action; when a certain degree of assistance is rendered the paretic muscle, the latter is enabled to exert its remaining power and thus to produce fusion of images. On this account prisms are very useful in paresis, since the muscles are stimulated by exercise, and contraction of the antagonistic muscles is prevented. The strength of the prismatic correction should be reduced as the paresis diminishes.

Prismatic and Stereoscopic Exercises.—Exercises with prisms or with the stereoscope are also advocated in paresis, and may be found useful in some cases. The methods are the same as applied in concomitant affections.

Occlusion of the Paralyzed Eye.—In those cases in which the diplopia cannot be overcome by prisms suitable for wearing as spectacles, we should cover the affected eye with an opaque disk, if diplopia causes much annoyance.

Muscle Stretching.—This consists in grasping the eyeball with forceps and rotating it forcibly a few times in the direction of action of the paralyzed muscle. This method, applied for one or two minutes every day, seems to exert a beneficial

effect in some cases, chiefly perhaps by preventing contraction of the antagonistic muscles. It is not advisable in recent paralysis. A local anæsthetic must be employed to prevent pain.

Operative Treatment.—This is permissible only in old paralysis in which there is decided contraction of the principal opposing muscle, and in which there is no hope of curing the paralysis. The frequency of indication for such treatment is diminished by the fact that in long-continued paralysis annoying subjective disturbances are usually absent. In those cases in which operation is apparently indicated the result is frequently disappointing. The most that can be expected is improvement of the strabismus and relief from diplopia in the more common directions of the eyes. Operation can be of no benefit unless there is some power left in the affected muscle. Advancement of the muscle may increase this power, but if the antagonistic contraction is very great, tenotomy of the latter muscle must be combined with the advancement of the paralyzed muscle. In paralysis of the superior oblique, as well as in that of the inferior rectus advancement of the latter muscle is the operation to be selected.

Paralyses of Associated Movements

A lesion situated above the nerve-nucleus cannot produce a *monocular* disturbance of motility. Any limitation of movement produced by a lesion so situated must be *binocular*. This limitation may consist in inability to turn the two eyes consensually to the right or to the left, or upward or downward; or all these motions may be normally performed, and yet the power of simultaneously contracting the two internal recti for convergence may be totally lacking.

Conjugate lateral deviation of both eyes to the right or left not infrequently occurs as a transitory symptom in cerebral hemorrhage. The cortical center for rotation of the two eyes to the right lies in the left hemisphere. Hence a destructive lesion in the left hemisphere causes a loss of power of deviation to the right, with consequent deviation of the eyes to the left; that is, *the eyes look towards the lesion.* This is just the opposite to what occurs in irritative lesions, such as give rise to epileptiform

convulsions. The spasmodic deviation produced by an irritative lesion may at any time be replaced by paralysis, if the lesion is of sufficient magnitude to produce destruction of tissue.

Conjugate deviation occurring in apoplectic attacks is a *distant* symptom—that is, the centers of ocular motion are not injured. The deviation probably results from suspension of function in the entire hemisphere (*Swanzy*). There being no stimulation of the affected side, the opposing muscles draw the eyes in the opposite direction. The function of the affected hemisphere may be restored, or if permanently injured the other hemisphere, through intimate association, comes to the rescue, and the deviation is overcome.

Although conjugate lateral deviation is known to result from a lesion situated in the cortex or in the optic radiations, it can not be said that all associated paralyses are due to lesions in this region. We do not know the situation of the lowest centers or nuclei which preside over binocular action. It appears from the result of autopsies that in the case of lateral movements a portion of the nucleus of the sixth nerve exercises this control, since fibers from this nucleus pass to the opposite internal rectus as well as to the external rectus of its own side. Thus it would seem that the nucleus of the sixth nerve on either side controls lateral movement to the corresponding side. Hence destruction of the nucleus at the point of origin of these two sets of fibers causes conjugate lateral paralysis. This symptom—*conjugate lateral paralysis*—is also sometimes produced by pressure upon the nerves by a lesion in the pons. In all these cases the deviation is opposite to that which occurs in cortical lesions; that is, the *eyes look away from the lesion.*

Paralysis of upward or downward movements of both eyes generally results from pressure by a tumor in the quadrigeminal region.

Paralysis of Convergence.—This may be complete or partial; in the latter case it resembles non-paralytic insufficiency of convergence, and in some cases a distinction may be impossible.

Complete paralysis of convergence consists in a total abolition of the converging power without loss, as a rule, of power in any of the individual muscles, although the latter may be implicated by extension of the morbid process. Accommodation, on

the other hand, usually participates in the paralysis, but without mydriasis. The eyes assume a position of parallelism or slight divergence, maintaining this position in near vision with resulting crossed diplopia.

The nucleus for convergence probably lies in the aqueduct of Sylvius, near the nuclei for the ciliary muscles. Hence in paralysis of convergence a lesion in this region is presupposed, as it is unlikely that a cortical lesion would produce this paralysis without giving rise to other and graver symptoms.

In the etiology of paralysis of convergence tabes holds the first place, this being the cause in the majority of cases which have been observed. Other causes are syphilis and poisoning by alcohol and tobacco.

Paralysis of Divergence.—This sometimes occurs in conjunction with paralysis of convergence, as manifested by homonymous diplopia in distant vision, together with crossed diplopia in near vision. *Paralysis of divergence* may also occur without paralysis of convergence, the etiology being the same as in the latter affection.

Treatment of Paralysis of Associated Movements.—This is such as is appropriate for the causal lesion, so far as that admits of cure. In paresis of convergence or of divergence the enfeebled action may be assisted by the use of prismatic glasses within the limits to which such glasses are subject.

The following authorities have been consulted in the preparation of the foregoing chapter:

Stevens, *Motor Apparatus of the Eyes.*

Howe, *Muscles of the Eyes.*

Maddox, *Ocular Muscles.*

Duane, *Extra-Ocular Muscles,* Posey and Spiller's Eye and Nervous System.

Fuchs, *Text Book of Ophthalmology.*

Landolt, *Anomalies of the Motor Apparatus of the Eyes,* Norris and Oliver's *System of Diseases of the Eye.*

Evans, *Congenital Defect of Abduction with Retraction of the Eyeball in Adduction,* Ophthal. Review, 1903.

Swanzy, *Eye Diseases and Eye Symptoms in their Relation to Organic Diseases of the Brain and Spinal Cord,* Norris and Oliver's *System of Diseases of the Eye.*

Posey, *Congenital Squint,* Trans. Am. Ophth. Soc., 1907; and *Paralysis of the Upward Movements of the Eyes,* Report Sec. on Ophth., College of Phys. of Phila., 1903.

APPENDIX

ALGEBRAIC FORMULAE

In order that we may have a proper knowledge of the various optical problems which are presented in ophthalmology we must study the elementary algebraic formulæ by which we trace the path of refracted rays of light.

Deviation Effected by a Prism

In Fig. 141 $B\ A\ C$ represents a section in the principal plane of a prism, of which $A\ (a)$ is the refracting angle. The line $O\ S\ S_1\ R$ is a ray passing through the prism in its principal

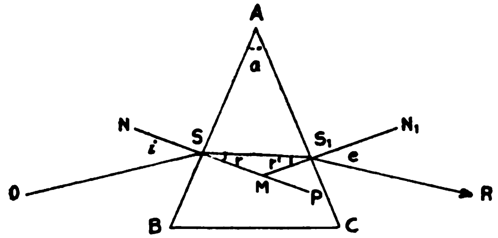


FIG. 141

plane; $N\ M$ is the normal at the point of incidence, and $N_1\ M$ is the normal at the point of emergence of the ray.

The reader who has even an elementary knowledge of geometry will readily understand the following equations:

$$S_1\ M\ P = a$$

[The angle formed by the intersection of two lines is equal to the angle formed by the intersection of two other lines perpendicular to the first two lines.]

$$S_1\ M\ P = r + r'$$

[The sum of two angles of a triangle is equal to 180° less the third angle.]

Therefore $r + r' = a$

The deviation of the ray at the first refraction is evidently equal to the difference between the angles of incidence and re-

fraction $(i - r)$, and the deviation at the second surface is similarly expressed by $e - r'$. The total deviation is expressed in the equation:

$$D = i - r + e - r',$$

or, since $r + r' = a$,

$$D = i + e - a$$

From this equation we see that the deviation effected by a prism is equal to the sum of the angles of incidence and emergence, less the refracting angle of the prism.

For the symmetrical ray—the ray of minimum deviation—i is equal to e, r is equal to r', and, consequently, $r = \frac{a}{2}$.

From this equation and from the equation for refraction, $sin\ i = n\ sin\ r$, we can replace r by its equivalent in terms of the refracting angle, a:

$$sin\ i = n\ sin\ \frac{a}{2}\ *$$

If we know the refractive index (n) and the refracting angle (a), we can ascertain the value of i from a table of sines. The minimum deviation is then determined from the equation

$$D = 2\,i - a$$

For the ray of perpendicular incidence i and r are each zero; therefore, $r' = a$

and
$$D = e - a$$

If we know the index and the refracting angle we can determine e from the equation

$$sin\ e = n\ sin\ r' = n\ sin\ a$$

We thus find the value of e from a table of sines and substitute this value in the equation

$$D = e - a$$

In this way the table (p. 30) has been constructed, giving the deviation effected by prisms of various refracting angles.

In constructing the table showing the deviation of prisms in terms of the prism diopter it is only necessary to take from a table of tangents the angle which corresponds to the tangent, as this is represented by the number of the prism. Thus the deviation effected by a prism of 1 △ is the angle whose tangent is 1, and so on.

*** If these angles are small we may replace the ratio of their sines by that of the angles themselves, and if $n = 1.5$ (the approximate index for glass), $sin\ i = n\ sin\ \frac{a}{2}$ becomes $i = \frac{3}{4}\ a$, and $D = \frac{a}{2}$. That is, for prisms of small refracting angle the deviation is about one-half of this angle.**

Relation between Conjugate Points in Refraction at a Spherical Surface

In deriving the algebraic equation between conjugate points in refraction at a spherical surface we take the condition shown in Fig. 142, as the typical case because it is convenient for us to regard the terms as positive when the surface is convex, and when the rays proceed from a real focus (O) and converge after refraction to a real focus (I).

The straight line $O\ I$ (the unrefracted ray) which passes through the center of the surface is the *axis*. All distances are measured on this line.

In the diagram $S\ A\ S$ represents a section of the convex refracting surface, and $S\ B_1\ S$ represents the wave front as it

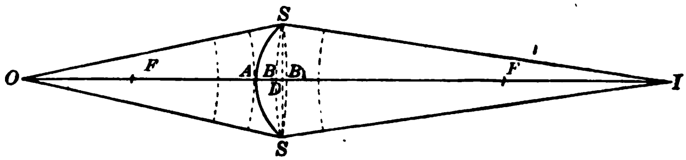


FIG. 142

would be at a certain time if the retarding medium were absent; but owing to this retarding medium the actual wave front at this time is $S\ B\ S$. While the wave would have advanced from A to B_1, in the rarer medium, it is so retarded by the dense medium that it advances only as far as B. These distances are inversely proportional to the velocity of light in the two media. If therefore n represents the refractive index of the first and n_1 that of the second medium, it is apparent that

$$n \times A\ B_1 = n_1 \times A\ B$$

It also appears from the diagram that

$$A\ B = A\ D - B\ D$$

and that

$$A\ B_1 = A\ D + D\ B_1$$

and therefore

$$n\ (A\ B + D\ B_1) = n_1\ (A\ D - D\ B)$$

or,

$$n \times D\ B_1 + n_1\ D\ B = (n_1 - n)\ A\ D \quad . \quad . \quad . \quad (a)$$

The distances $D\ B_1$, $D\ B$ and $A\ D$ are not practically measurable, but they express respectively the curvature of the incident wave, of the refracted wave and of the refracting surface.

If the arc $S\ B_1\ S$ is infinitesimal, the bending or curvature of this arc is measured by the perpendicular distance $D\ B_1$.

Similarly, under the same conditions the curvatures of the arcs $S\ B\ S$ and $S\ A\ S$ are measured by $D\ B$ and $A\ D$ respectively.

As the size of the arc increases the perpendicular distance cannot be taken as the exact measurement of the curvature, but for the small pencils of light, such as enter the pupil of the eye, the error arising from these measurements is negligible.

But there are other and more convenient measurements which express the curvatures of the waves and of the surface—the reciprocals of their radii of curvature. Thus the curvature of the incident wave is expressed by $\frac{1}{O\ S}$; the curvature of the refracted wave is expressed by $\frac{1}{IS}$; and the curvature of the refracting surface by $\frac{1}{r}$, r being the radius of this surface. Hence, these expressions could be substituted in equation (a) for $D\ B_1$, $D\ B$ and $A\ D$, respectively; but here still another substitution must be made which is only approximately correct. It must be borne in mind that the distances $O\ A$, $O\ S$, $I\ S$ and $I\ A$ are all very great in proportion to the arc $S\ A\ S$, and that consequently in actual measurement there would be very little difference between $O\ S$ and $O\ A$, and between $I\ S$ and $I\ A$*. These distances, $O\ A$ and $I\ A$, measured on the axis, may, therefore, be substituted for $O\ S$ and $I\ S$, respectively, and consequently for $D\ B_1$ and $D\ B$ in equation (a), which, therefore becomes

$$\frac{n}{A\ O} + \frac{n_1}{A\ I} = \frac{(n_1 - n)}{r}$$

or by substituting f and f' for $O\ A$ and $A\ I$, respectively,

$$\frac{n}{f} + \frac{n_1}{f'} = \frac{(n_1 - n)}{r}. \qquad (1)$$

This equation, expressing the relation between conjugate focal distances (f and f') is, as has been shown, only approximately correct. It is, however, sufficiently so for the purposes of ophthalmological study, although it would be far from sufficient for the construction of microscopes or other instruments in which spherical aberration could not be neglected.

Within these prescribed limits this equation is applicable for all cases of refraction at a spherical surface.

When n_1 is greater than n, and r is positive, the refraction takes place in the passage of the wave from a rarer to a denser medium at a convex surface; when n_1 is less than n and r positive, the refraction is that of a wave passing from a denser to

*The proper proportions can not be represented diagrammatically.

a rarer medium at a convex surface; when r is negative, the refracting surface is concave; and when r is infinite the surface is plane.

Principal Foci and Focal Distances.—When O is so far distant from the surface that the wave may be regarded as plane and the rays as parallel, the distance $A\ O$ (f) must be regarded as infinite, and consequently $\frac{n}{f}$ is zero. By making this substitution in equation (1) we derive for the corresponding value of f' the equation

$$f' = \frac{n_1 r}{n_1 - n}.$$

This equation determines the focusing point for rays that are parallel before refraction. The distance ($A\ F'$) of this point from the surface is the *posterior* (or second) *principal focal distance*; it is denoted by the letter F', the value of F' being derived from the equation

$$F' = \frac{n_1 r}{n_1 - n}.$$

The point at which parallel rays are focused, as determined by this equation, is called the *posterior* (or second) *principal focus* (F').

Similarly, if f' is infinite in equation (1), we have

$$f = \frac{n \cdot r}{n_1 - n}.$$

This equation determines the point of origin of rays which become parallel after refraction. The distance $A\ F$ is the *anterior* (or first) *principal focal distance*; it is denoted by the letter F. The point (F) from which rays must diverge in order that they may be parallel after refraction is the *anterior* (or first) *principal focus*. Since

$$F = \frac{n\ r}{n_1 - n}, \text{ and } F' = \frac{n_1\ r}{n_1 - n}$$

equation (1) becomes

$$\frac{n}{f} + \frac{n_1}{f'} = \frac{n}{F} = \frac{n_1}{F'}. \qquad (2)$$

Equation (2) may also be written in the form

$$\frac{F}{f} + \frac{F'}{f'} = 1. \qquad (3)$$

When the index of the first medium is unity, as in air, equation (2) becomes

$$\frac{1}{f} + \frac{n}{f'} = \frac{1}{F}.$$

If l represents the distance of any conjugate focus from the anterior principal focus, and l' the distance of the corresponding posterior conjugate from the posterior principal focus, f is equal to $l + F$, and f' is equal to $l' + F'$.

By substituting these values for f and f' in any of the foregoing equations we derive the equation

$$l\, l' = F\, F' \quad (4)$$

Equations (*1*), (*2*), (*3*) and (*4*) constitute all of the commonly used equations expressing the relation between conjugate points, but there remains one other form of this relation which will be required in the investigation of the refraction by the several surfaces of the eye.

For the derivation of this equation we use Fig. 143. $B_1\, O\, A_1$ represents a half section of the incident pencil, while $B_1\, I\, A_1$

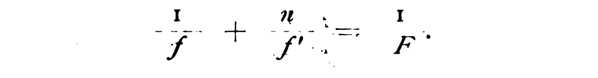


FIG. 143

represents the corresponding refracted pencil. The angle $B_1\, O\, A_1$ (a) represents the divergence of the incident pencil, while the convergence of the refracted pencil is represented by $B_1\, I\, A_1$ (*180* $- a_1$).

The perpendicular $B_1\, A_1$ (which we call b) represents the principal plane. Then

$$f\ (O\, A_1) = \frac{b}{\tan a}, \text{ and } f'\ (A_1\, I) = \frac{b}{\tan\,(180 - a_1)}$$

$$\text{or } f' = -\frac{b}{\tan a_1}.$$

By substituting these values for f and f' in equation (3) we derive

$$\frac{n \tan a}{b} - \frac{n_1 \tan a_1}{b} = \frac{n}{F} \quad (5)$$

We also make use of the relation between the angles of divergence of the incident and refracted pencils in comparing the size of the object and its image. If we express the relative

size of the object and its image by means of their respective distances from the nodal point, we have the equation

$$\frac{o}{i} = \frac{f + r}{f' - r} \quad (6)^*$$

From equation (1) we derive the value of r in terms of n, n_1, f and f'

$$\left(r = \frac{(n_1 - n) f f'}{n f' + n_1 f}\right),$$

and substitute this value in (6); whence by reduction we derive

$$\frac{o}{i} = \frac{n_1 f}{n f'}.$$

But since

$$\frac{f'}{f} = - \frac{\tan a}{\tan a_1}, \text{ we have } \frac{o}{i} = - \frac{n_1 \tan a_1}{n \tan a}.$$

Since the image in one refraction may become the object in a successive refraction, we may express the relation between an object and its successive images by the following equation:

$$- o \,.\, n \,.\, tan\ a = i_1 .\ n_1 .\ tan\ a_1 = i_2 .\ n_2 .\ tan\ a_2 = i_3 .\ n_3 .\ tan\ a_3 = i_4 .\ n_4 .\ tan\ a_4,$$

and so on for any number of refractions.† If after the last refraction the image is of the same size as the original object and on the same side of the axis we have the equation

$$n \,.\, tan\ a = n_4\ tan\ a_4 \quad (7)$$

This equation is used for determining the principal points of a compound optical system.

Relation between Conjugate Points in Refraction by Lenses

Refraction by a biconvex lens is illustrated in Fig. 144, in which a wave diverging from O is represented as converging to I_1 as the result of refraction at the first surface of the lens, and as the result of the second refraction the wave which is converging to I_1 is rendered more convergent and is focused at I_2.

This is only one of several conditions that may obtain; the wave may remain divergent after the first refraction, being rendered convergent by the second refraction (illustrated by revers-

* Page 43.

† The first term of this equation is negative because the object is inverted with respect to the image; in the subsequent terms the positive signs indicate that the object and image lie on the same side of the optic axis.

ing the course of the rays in the diagram); the wave may remain divergent or it may be plane after the two refractions; it may be plane or convergent before refraction, its convergence being increased by the refraction.

The condition of a diverging pencil, brought to a real focus by the two combined refractions, as illustrated, is taken as a

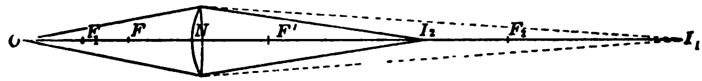


FIG. 144

typical case for the derivation of the formula, because it is more convenient for us to regard the focal distances as positive when the foci are real, as in the diagram.

Applying formula (1) to the first refraction, we derive the equation

$$\frac{1}{ON} + \frac{n}{NI_1} = \frac{n-1}{r} = \frac{1}{F_1},$$

in which n, the refractive index of the lens, is greater than that of the surrounding air; r is the radius of curvature and F_1 is the distance ($N\ F_1$) of the lens from the principal focus F_1 of this refraction.

Applying formula (1) to the second refraction and remembering that as regards this refraction $N\ I_1$ is negative, as is also r_1, the radius of the surface, we derive

$$-\frac{n}{NI_1} + \frac{1}{NI_2} = \frac{1-n}{-r_1} = \frac{n-1}{r_1} = \frac{1}{F_2},$$

F_2 being the distance ($N\ F_2$) from the lens to the principal focus F_2 of the second refraction.

Adding these two equations and replacing $O\ N$ and $N\ I_2$ by f and f', respectively, we derive

$$\frac{1}{f} + \frac{1}{f'} = (n-1)\left(\frac{1}{r} + \frac{1}{r_1}\right) = \frac{1}{F_1} + \frac{1}{F_2}. \quad (8)$$

If we make f infinite in the above equation, we derive

$$\frac{F_1\ F_2}{F_1 + F_2}$$

as the corresponding value for the second principal focal distance, and if we make f' infinite, we derive this same value for the first principal focal distance. Hence, in a lens the two princi-

pal focal distances are equal and (in thin lenses) the reciprocal of this distance ($\frac{1}{F}$) is equal to the sum of the reciprocals of the principal focal distances

$$\left(\frac{1}{F_1} + \frac{1}{F_2}\right)$$

of the two separate refractions.

If we make this substitution, equation (8) becomes

$$\frac{1}{f} + \frac{1}{f'} = \frac{1}{F} \qquad (9)$$

which is the form in which the equation between conjugate points for lens refraction is usually written.

If either r or r_1 is infinite, that is, if one surface of the lens is plane and the other convex, equation (8) becomes

$$\frac{1}{f} + \frac{1}{f'} = \frac{n-1}{r}. \qquad (10)$$

By the appropriate modification of the signs of r and r_1 we can apply the foregoing equations to plano-concave, convexo-concave and biconcave lenses.

But when the thickness of a lens is appreciable as compared with its focal length these equations are not applicable, since the distance between the two surfaces has been disregarded in the derivation of the formulæ. A thick lens constitutes a compound optical system and its cardinal points are determined by the method next to be given for such a system.

The Cardinal Points of the Schematic Eye

Listing in deducing his schematic eye used the method of Gauss, in which the path of any refracted ray is determined by means of analytical geometry. Helmholtz adopted a different

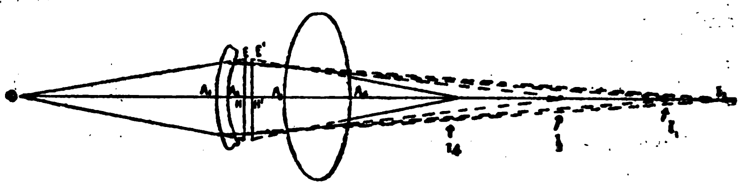


FIG. 145

method. He determined first the cardinal points of the corneal refraction, then the cardinal points of the crystalline lens and combined these two systems, determining thereby the cardinal points of the combination. The process is necessarily tedious;

whatever method is used, but that which I here give has the advantage that the diagrammatic illustration is easily understood and that only an elementary knowledge of mathematics is demanded.

The refractions which occur at the several surfaces of the eye are illustrated in Fig. 145.

Applying equation (5) to the first refraction (at the anterior surface of the cornea) we have

$$\frac{\tan a}{b_1} - \frac{n_1 \tan a_1}{b_1} = \frac{1}{F_1}. \quad (5a)$$

Applying equation (5) to the second refraction (at the posterior surface of the cornea) we have

$$\frac{n_1 \tan a_1}{b_2} - \frac{n_2 \tan a_2}{b_2} = \frac{n_1}{F_2}. \quad (5b)$$

In the third refraction (at the anterior surface of the crystalline lens) we have

$$\frac{n_2 \tan a_2}{b_3} - \frac{n_3 \tan a_3}{b_3} = \frac{n_2}{F_3}. \quad (5c)$$

And in the fourth refraction,

$$\frac{n_3 \tan a_3}{b_4} - \frac{n_4 \tan a_4}{b_4} = \frac{n_3}{F_4}. \quad (5d)$$

It appears also from Fig. 144

that $[A_2 B_2]\ b_2 = [A_1 B_1]\ b_1 - A_1 A_2 \tan (180 - a_1)$.

Similarly

$$b_3 = b_2 - A_2 A_3 \tan (180 - a_2)$$

and

$$b_4 = b_3 - A_3 A_4 \tan (180 - a_3)$$

Replacing the tangent of 180° minus the angle by minus the tangent of the angle, and writing t_1, t_2 and t_3 for the intervals between the surfaces, we have the following equations:

$$b_2 = b_1 + t_1 \tan a_1 \ (11a)$$
$$b_3 = b_2 + t_2 \tan a_2 \ (11b)$$
$$b_4 = b_3 + t_3 \tan a_3 \ (11c)$$

and also

$$b_1 = f . \tan a$$

By making the proper substitutions in these two sets of equations we can eliminate the intermediate terms and derive a relation between any point and its conjugate after the four refractions, but as our desire is only to apply this process to the

eye, not to deduce the general algebraic formula, which is complicated, we proceed at once with the arithmetical substitutions.

The following table gives the values which may be accepted as average measurements of the normal human eye.

RADII OF CURVATURE

Anterior surface of the cornea	7.8 mm.	(r_1)
Posterior surface of the cornea	6 mm.	(r_2)
Anterior surface of the lens	10 mm.	(r_3)
Posterior surface of the lens	6 mm.	(r_4)

INDICES		THICKNESSES	
Cornea	1.377 (n_1)	1 mm.	(t_1)
Aqueous humor	1.337 (n_2)	2.6 mm.	(t_2)
Lens	1.437 (n_3)	4 mm.	(t_3)
Vitreous body	1.337 (n_4)		

By numerical substitution we derive the following values:

$$\frac{1}{F_1} = \frac{n_1 - 1}{r_1} = 0.0484\,; \quad \frac{n_1}{F_2} = \frac{n_2 - n_1}{r_2} = -\,0.0066\,;$$

$$\frac{n_2}{F_3} = \frac{n_3 - n_2}{r_3} = 0.01\,; \quad \frac{n_3}{F_4} = \frac{n_4 - n_3}{-\,r_4} = 0.0168\,;$$

$$\frac{t_1}{n_1} = 0.7262\,; \quad \frac{t_2}{n_2} = 1.9446\,; \quad \frac{t_3}{n_3} = 2.7816.$$

Placing the value of $\frac{1}{F_1}$ here obtained in equation (5 a) and assigning to n_1 (1.377), its value, we derive

$$\tan a_1 = -\,.0351\, b_1 + .7262 \tan a$$

We now place this equivalent for tan a_1 in equation (11 a) and substitute for t_1 its value. The result is

$$b_2 = .9649\, b_1 + .7262 \tan a$$

We next proceed to the second refraction and substitute this value of b_2 and also the value found for tan a_1 and for $\frac{{}_1n}{F_2}$ in equation (5 b), as follows:

$$-\,.0484\, b_1 + \tan a - n_2 \tan a_2 = -\,.0066\,(.9649\, b_1 + .7262 \tan a)$$

whence by reduction

$$+\, n_2 \tan a_2 = -\,.0421\, b_1 + 1.0048 \tan a.$$

Similarly in the third refraction we have

$$-.0421\ b_1 + 1.0048\ tan\ a - n_3\ tan\ a_3 = .01\ b_3.$$

and

$$b_3 = .9649\ b_1 + .7262\ tan\ a + 1.9466\ (-.0421\ b_1 + 1.0048\ tan\ a)$$

or

$$b_3 = .8831\ b_1 + 2.6801\ tan\ a$$

Therefore

$$-.0421\ b_1 + 1.0048\ tan\ a - n_3\ tan\ a_3 = .0088\ b_1 + .0268\ tan\ a$$

or

$$n_3\ tan\ a_3 = -.051\ b_1 + .978\ tan\ a.$$

In the fourth and last refraction we have

$$b_4 = .8831\ b_1 + 2.6801\ tan\ a + 2.7816\ (-.051\ b_1 + .978\ tan\ a)$$

or

$$b_4 = .7415\ b_1 + 5.4005\ tan\ a \quad (\mathbf{12})$$

Substituting this value of b_4 and the values found for n_3 tan a_3 and for $\frac{n_3}{F_4}$ in equation (5d), we derive

$$-.051\ b_1 + .978\ tan\ a - n_4\ tan\ a_4 = .0168\ (.7415\ b_1 + 5.4005\ tan\ a)$$

and by reduction,

$$-n_4\ tan\ a_4 = .0634\ b_1 - .8873\ tan\ a$$

If b_1 is replaced by its equivalent f *tan a*, this equation becomes

$$-n_4\ tan\ a_4 = .0634\ f\ tan\ a - .8873\ tan\ a \quad (\mathbf{13})$$

in which f is the distance of the anterior conjugate point from the anterior surface of the cornea and *tan a* and *tan* a_4 are the tangents of the angles which any ray from this point makes with the optic axis before and after refraction by the four surfaces of the eye.

From equations (12) and (13) we can determine all the cardinal points of the eye.

Anterior Principal Focus.—For finding the position of this point we use equation (13). Since rays proceeding from the anterior focus are parallel to the optic axis after refraction, a_4 becomes zero (or 180°) and *tan* $a_4 = o$, and if we divide by *tan a* the equation becomes

$$.0634\ f = .8873$$

or

$$f = 13.99$$

The distance of the anterior focus from the anterior surface of the cornea is therefore 13.99 *mm.*

Posterior Principal Focus.—For finding the position of this point we use equations (12) and (13). Since rays which meet at the posterior focus are parallel to the optic axis before refraction, a is for this point zero (or 180°) and $tan\ a = o$. Equation (12) therefore becomes

$$b_4 = .7415\ b_1$$

Also when $tan\ a = o$ equation (13) becomes (writing b_1 *for* $f\ tan\ a$)

$$-\ n_4\ tan\ a_4 = .0634\ b_1$$

and, since

$$\tan (180 - a_4) = -\tan a_4 = \frac{b_4}{f_4},\ \frac{n_4\ b_4}{f_4} = .0634\ b_1.$$

Substituting for b_4 its value .7415 b_1, as above deduced, we have

$$\frac{1.337 \times .7415\ b_1}{f_4} = .0634\ b_1,$$

and by reduction

$$f_4 = 15.62$$

The distance of the posterior focus from the posterior surface of the crystalline lens is therefore 15.62 *mm*, and since this surface lies 7.6 *mm* behind the anterior surface of the cornea, the posterior focus lies 23.22 *mm* behind the latter surface.

First Principal Point.—We determine the position of this point from equation (13). We recall that the two principal points are conjugate points such that a ray directed towards a point in one principal plane appears after refraction to come from a point on the same side of and equally distant from the axis in the other principal plane; that is, the determining conditions of the principal points are: (1) that they must be conjugate; and (2) that an object situated in one of these planes and its image situated in the other plane must be equal.

The condition of equality of object and image (*the two lying on the same side of the axis*) after four refractions is

$$tan\ a = n_4\ tan\ a_4$$

as we have learned from equation (7). If we apply this condition to equation (13), we derive

$$.0634\ f = -\ .1127$$

or

$$f = -\ 1.77$$

The first principal point therefore lies 1.77 *mm* behind the anterior surface of the cornea.

Second Principal Point.—In equation (12) we write $-f_4\ tan\ a_4\ [f_4\ tan\ (180 - a)]$ for b_4 and multiply both terms by n_4:

$$-n_4\ tan\ a_4\ f_4 = .7415\ n_4 \times f\ tan\ a + 5.4005 \times n_4 \times tan\ a.$$

Since $n_4 \tan a_4 = \tan a$, and since f (which is conjugate to f_4) is $-$ 1.77 *mm*, as has been found for the first principal point, we derive

$$- f_4 = - 1.3124\, n_4 + 5.4005\, n_4$$

By reduction and substitution of its value (1.337) for n_4 we derive

$$f_4 = - 5.46$$

The second principal point therefore lies 5.46 *mm* in front of the posterior surface of the crystalline lens and consequently it lies 2.14 *mm* behind the anterior surface of the cornea.

First Nodal Point.—Since the nodal rays pass through a system without deviation the nodal points are determined by the condition of equality of a and a_4. We impose this condition in equation (13) and derive

$$- 1.337 = .0634\, f - .8873$$
$$f = - 7.09$$

The first nodal point lies 7.09 *mm* behind the anterior surface of the cornea.

Second Nodal Point.—In equation (12) we write $- f_4 \tan a_4$ for b_4 and $f \tan a$ for b_1.

$$- f_4 \tan a_4 = .7415\, f \tan a + 5.4005 \tan a$$

Since $\tan a_4 = \tan a$, and f, the value found for the first nodal point, is $-$ 7.09, we deduce

$$f_4 = - .14$$

The second nodal point lies .14 *mm* in front of the posterior surface of the crystalline lens, or it lies 7.46 *mm* behind the anterior surface of the cornea.

Principal Focal Distances.—In accordance with the demonstration of Gauss, we can express the relation between conjugate points after refraction by a compound system of any number of surfaces by the same formula which expresses this relation after a simple refraction; but in order to do this we must measure the anterior conjugates from the first principal point and the posterior conjugates from the second principal point.

The anterior principal focal distance of the eye is therefore 15.76 *mm* (13.99 + 1.77) and the posterior focal distance is 21.08 *mm* (15.62 + 5.46).

With these values for F and F' respectively we may express the relation between conjugate points by the equation

$$\frac{F}{f} + \frac{F'}{f'} = 1,$$

or by any of the other forms in which we write the relation between conjugate points after a single refraction.

SUMMARY

From summit of cornea to first principal point.........	1.77 *mm*
From summit of cornea to second principal point......	2.14 *mm*
From summit of cornea to first nodal point............	7.09 *mm*
From summit of cornea to second nodal point.........	7.46 *mm*
From summit of cornea to anterior focus..............	13.99 *mm*
From summit of cornea to posterior focus............	23.22 *mm*
Anterior focal distance (measured from first principal point)......................................	15.76 *mm*
Posterior focal distance (measured from second principal point)..................................	21.08 *mm*

Cardinal Points of a Thick Lens

In the same way in which we determine the cardinal points of the eye we can find the cardinal points of a thick lens; but as in the latter case there are only two refractions we require only equations (*5a*), (*5b*), and (*11a*).

Relation between Variation of Curvature and Astigmia

In the diagram (Fig. 146) the portion above the optic axis represents the meridian of greatest curvature and the portion

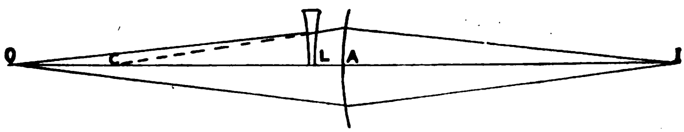


FIG. 146

below the axis represents the meridian of least curvature of an asymmetrical surface. In the meridian of greatest curvature C is conjugate to I, while in the meridian of least curvature O is conjugate to I. In order that rays from a point O may be focused at I their divergence must be increased in the meridian of greatest curvature so that in this meridian they appear to proceed from C.

In the refraction by the lens which thus overcomes the astigmia O and C are conjugate points and the focal length of this lens is determined by the equation

$$\frac{1}{OL} - \frac{1}{CL} = \frac{1}{F} \quad \text{(d)}.$$

In the refraction by the asymmetrical surface we have for the meridian of greatest curvature the equation

$$\frac{1}{AC} + \frac{n}{AI} = \frac{1}{F_1},$$

in which F_1 is the anterior focal distance of this refraction. In the meridian of least curvature we have the equation

$$\frac{1}{AO} + \frac{n}{AI} = \frac{1}{F_2},$$

in which F_2 is the anterior focal distance of this refraction.

By subtraction we derive

$$\frac{1}{AO} - \frac{1}{AC} = \frac{1}{F_2} - \frac{1}{F_1}.$$

If we disregard the distance of the correcting lens from the surface equation (d) becomes

$$\frac{1}{AO} - \frac{1}{AC} = \frac{1}{F}$$

and

$$\frac{1}{F} = \frac{1}{F_2} - \frac{1}{F_1}.$$

Therefore, if we disregard the distance of the correcting lens from the surface the dioptric power$\left(\frac{1}{F}\right)$ of this lens is equal to the difference of the reciprocals of the anterior focal distances in the two principal meridians.

The reciprocals of the anterior focal distances of the principal meridians of the cornea $\left(\frac{1}{F_1} \text{ and} \frac{1}{F_2}\right)$ are analogous to the expression $\left(\frac{1}{F}\right)$ which determines the dioptric power of a lens, and it is customary to speak of the reciprocal of the anterior focal length of the cornea as its dioptric power. This is convenient in ophthalmometry, but we should not forget that the diopter is a unit of lens measurement only. We can not apply it in general calculations to single surface refraction, in which the two focal distances are unequal, or to refraction by a thick lens.

It is in this way that we measure astigmia by ophthalmometry. The error which we incur by neglecting the distance of the correcting lens from the eye varies greatly with the refraction of the eye, for, as is apparent from the diagram, the error is greater according as the distances $A\ O$ and $A\ C$ are less in proportion to $A\ L$.

The error is least in simple astigmia, when one meridian of the eye is emmetropic and the other hyperopic or myopic.

If under this condition the astigmia at the cornea is *1 D*, the convex correcting lens placed 15 *mm* from the cornea is .98 D, $\left(\frac{1}{1000 + 15}\right)$; if the astigmia at the cornea is 3 D, the convex correcting lens is 2.87 D $\left(\frac{1}{333 + 15}\right)$, and so on.

If a concave lens is required to correct the faulty meridian 1 D at the cornea corresponds to a lens correction of 1.01 D $\left(\frac{1}{1000 - 15}\right)$, 3 D at the cornea corresponds to a lens correction of 3.14 D $\left(\frac{1}{333 - 15}\right)$, and so on.

If in addition to the 3 D of astigmia the eye has 5 D of myopia (at the cornea), we determine the strength of the correcting lens as follows: We first find the distance *A C* which is conjugate to *A O* (200 *mm*) when there is 3 D of astigmia at the cornea

$$\frac{1}{200} - \frac{1}{F} = .003$$

$$f = 125$$

The distance *A C* is therefore 125 *mm*. We now ascertain the strength of the correcting lens from the equation

$$\frac{1}{200 - 15} - \frac{1}{125 - 15} = \frac{1}{F}.$$

From this equation we find the value of $\frac{1}{F}$ to be .0036; or expressed in terms of the diopter, $D = 3.6$. The astigmia which measures 3 D at the surface of the cornea therefore requires a lens of 3.6 D (15 *mm* from the cornea) when there coexists with the astigmia 5 D of myopia.

In the same way we can find the difference between the astigmia at the cornea and the required correcting lens in other states of refraction. The result of such calculation for various degrees of ametropia is here given.

Simple Hyperopic Astigmia

At the cornea	15 *mm* from the cornea
1 D	.98 D
3 D	2.87 D
6 D	5.49 D

Simple Myopic Astigmia

1 D	1.01 D
3 D	3.14 D
6 D	6.51 D

Astigmia with 5 D of Hyperopia

1 D	.84 D
3 D	2.50 D
6 D	4.70 D

Astigmia with 10 D of Hyperopia

1 D	.64 D
3 D	2.04 D
6 D	4.05 D

Astigmia with 5 D of Myopia

At the cornea	15 *mm* from the cornea
1 D	1.17 D
3 D	3.60 D
6 D	7.66 D

Astigmia with 10 D of Myopia

1 D	1.36 D
3 D	4.2 D
6 D	8.8 D

Astigmia with 15 D of Myopia

1 D	1.5 D
3 D	4.6 D
6 D	10 D

From this table we see that in a high degree of symmetrical ametropia combined with a high degree of astigmia we must look for a marked difference between the subjective error and the ophthalmometric record.

Ophthalmometric Determination of Astigmia of the Crystalline Lens

The rays of light which form the image reflected from the anterior surface of the lens are refracted as they enter and as they emerge from the cornea; and the rays which form the image reflected from the posterior surface are refracted not only at the

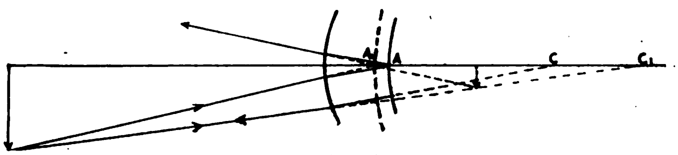


FIG. 147

cornea, but also at the anterior surface of the lens. The radii of the surfaces of the lens as they are modified by refraction are called the *apparent radii.*

The effect of these refractions on the anterior lens surface regarded as a mirror is shown in Fig. 147. The surface is displaced forward from A to A_1 and the center is displaced backwards from C to C_1. In the corneal refraction A and A_1 are conjugate points, as are also C and C_1.

By applying the equation for conjugate points

$$\left(\frac{1}{f} + \frac{n}{f'} = \frac{1}{F}\right)$$

on the basis of a radius of 7.8 *mm* for the cornea, a distance of 3.5 *mm* from the anterior surface of the cornea to the lens, and a

refractive index of 1.337 for the aqueous, I have derived the following relation between the apparent and actual radii.

Radius	Apparent Radius	Magnification
8.5 *mm*	11.6 *mm*	1.36
9 "	12.6 "	1.40
9.5 "	13.7 "	1.44
10 "	14.8 "	1.48
10.5 "	16 "	1.52
11 "	17.3 "	1.57
11.5 "	18.6 "	1.61
12 "	20.1 "	1.67
12.5 "	21.6 "	1.73

In order to ascertain the amount of error which might be incurred by basing the recording scale of the ophthalmometer upon the foregoing relations, I have determined the variation of refractive effect which occurs with the ordinary variations in the curvature of the cornea and in the distance between the cornea and the lens.

(1). *If the distance between the surfaces is 3.5 mm, while the radius of the cornea is 8.4 mm, I derive the following relations:*

Apparent Radius	Radius
12.6 *mm*	9.3 *mm*
16 "	10.9 "
20.1 "	12.5 "

As in ophthalmometry of the cornea the reciprocal of the anterior focal length $\left(\frac{1}{F}\right)$ is taken as the dioptric equivalent of the corneal refraction, so, as I shall subsequently show, the same expression represents approximately the dioptric equivalent (for the purpose of measuring astigmia) of the anterior surface of the lens. By thus expressing the dioptric value we make the following comparison:

Apparent Radius	Cornea 7.8 *mm* Radius	Cornea 8.4 *mm* Radius
12.6 *mm*	9 *mm* (8.3 D)	9.3 *mm* (8 D)
20.1 *mm*	12 *mm* (6.2 D)	12.5 *mm* (6 D)
Difference in diopters	2.1 D	2 D

From this we see that if a difference of three millimeters of radius, as determined in the two principal meridians, should occur, the error which would result from using a scale constructed on average measurements would be only one-tenth of a diopter.

If the radius of the cornea were 7.8 *mm* in one meridian and 8.4 *mm* in the other—that is, if there were 3 D of corneal as-

tigmia, and if the anterior surface of the lens were symmetrical, about .25 D of apparent astigmia in the opposite sense as the corneal astigmia would be produced. If the radius of the lens surface varied in the different meridians between the limits above shown, the astigmia would be overestimated or underestimated by about .25 D.

(2) *I next apply the same method to ascertain the possible error when the radius of the cornea is 7.3 mm (46 D), while the distance from the cornea to the lens remains 3.5 mm.*

Apparent Radius	Cornea 7.3 *mm* Radius	Cornea 7.8 *mm* Radius
12.6 *mm*	8.6 *mm* (8.7 D)	9 *mm* (8.3 D)
20.1 *mm*	11.5 *mm* (6.5 D)	12 *mm* (6.2 D)
Difference in diopters	2.2 D	2.1 D

As before, the error from using a scale constructed with average measurements is negligible as long as the cornea is symmetrical; if the radius of the cornea were 7.8 *mm* (43D) in one meridian and 7.3 *mm* (46 D) in the other, the resulting 3 D of corneal astigmia would entail an error of from .25 D to .4 D in the measurement of the lens. This error is slightly more than that which would result on the basis of the larger radius (8.4 *mm*), but we should get sufficient accuracy by assuming that 3 D of corneal astigmia would produce an apparent opposite astigmia of .37 D, or that *each diopter of corneal astigmia would produce an apparent opposite astigmia of .12 D.*

(3) *With an average radius of the cornea (7.8 mm) what would be the error from variation in the distance between the cornea and the lens?* Proceeding as before, I find these relations:

	Distance from Cornea to Lens		
Apparent Radius	3 *mm* Radius	3.5 *mm* Radius	4 *mm* Radius
12.6 *mm*	9.2 *mm* (8.1 D)	9 *mm* (8.3 D)	8.7 *mm* (8.6 D)
20.1 *mm*	12.3 *mm* (6.1 D)	12 *mm* (6.2 D)	11.6 *mm* (6.4 D)
Difference in diopters	2 D	2.1 D	2.2 D

The error arising from variation in the depth of the anterior chamber would not, therefore, exceed one-tenth of a diopter in a variation of three millimeters of radius.

(4) The greatest error in the measurement of the actual radius would occur if we had a large radius of the cornea combined with a shallow anterior chamber or a small radius of the cornea with a deep anterior chamber. In order to determine the possible error in the measurement of astigmia I have applied the formula for conjugate points *(a) with a corneal radius of 8.4 mm and a distance of 3 mm between the two surfaces and*

(b) with a corneal radius of 7.3 mm and a distance of 4 mm between the surfaces. In this way I derive the following relations:

Radius of cornea, 8.4 *mm*; distance between surfaces, 8 *mm*		Radius of cornea, 7.8 *mm*; distance between surfaces, 3.5 *mm*	Radius of cornea, 7.3 *mm*; distance between surfaces, 4 *mm*.
Apparent Radius	Radius	Radius	Radius
12.6 *mm*	9.5 *mm* (7.8 D)	9 *mm* (8.3 D)	8.3 *mm* (9 D)
20.1 mm	12.8 *mm* (5.8 D)	12 *mm* (6.2 D)	11 *mm* (6.8 D)
Difference in diopters	2. D	2.1 D	2.2 D

A review of the foregoing relations shows that although we could not rely upon average measurements for determining the exact radius of curvature of the anterior surface, such average measurements would be sufficient for the construction of a scale for measuring the astigmia resulting from asymmetry of this surface. Furthermore, when we recall the fact that the radius of the cornea very rarely differs by more than *one millimeter* in the two principal meridians and that this amount of difference in the anterior surface of the lens produces only two-thirds of a diopter of astigmia, it is apparent that such a degree of asymmetry of this surface as ordinarily occurs gives rise to a very small amount of astigmia.

In view of the unimportance of the anterior surface of the lens as a factor in the etiology of astigmia it is useless to enter into the investigation of the slight distorting effect which corneal astigmia would have upon the principal meridians of the anterior lens surface when the meridians of the corneal and lenticular astigmia are obliquely inclined.

The apparent radius of the posterior surface of the lens does not appreciably differ from the actual radius. By applying the formula for conjugate foci to the two refractions, using the

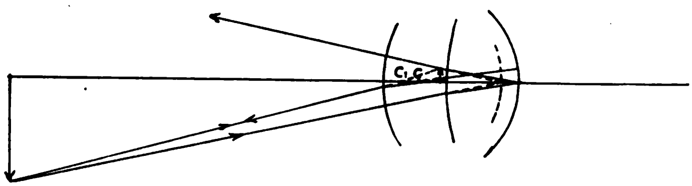


FIG 148

data of the schematic eye, I have found that the surface and its center are each displaced forward about two-tenths of a millimeter, so that the curvature of the apparent surface is the same as that of the actual surface (Fig. 148).

Relation between Astigmia produced at the Anterior Surface of the Crystalline Lens and the Correcting Lens Placed in front of the Cornea.—The astigmia which results

from asymmetry of the anterior lens surface is expressed by the difference between the reciprocals of the anterior focal lengths in the principal meridians $\left(\frac{1}{F_2} - \frac{1}{F_1}\right)$, as in corneal astigmia, but the application of the formula for conjugate points shows that the correcting lens, if placed in contact with the cornea, would be n (1.337) times the dioptric value of the astigmia at the asymmetric surface, provided we neglect the distance between the crystalline lens and the cornea. But this distance cannot be disregarded without appreciable error. I have determined from the equation for conjugate points the correcting lens which would be required, using the measurements of the schematic eye, for various degrees of asymmetry of the anterior lens surface in simple astigmia, in hyperopia of 5 D, and in myopia of 10 D, and I have found that the correcting lens placed in contact with the cornea is very nearly expressed in diopters by the formula $\frac{1}{F_2} - \frac{1}{F_1}$, as in corneal astigmia.

Relation between Astigmia produced at the Posterior Surface of the Crystalline Lens and the Correcting Lens Placed in front of the Cornea.—In deducing this relation we first have to find the equivalent lens if it were placed in front of the anterior surface of the crystalline lens and from this determine the lens which would be required in front of the cornea, as in the previous case. If we could neglect the distance from the posterior lens surface to the cornea, the correcting lens would be expressed by the difference of dioptric power in the two principal meridians multiplied by the refractive index of the crystalline lens $\left(\frac{n_2}{F_2} - \frac{n_2}{F_1}\right)$; but, owing to the distance at which the lens must be removed from the surface under measurement, a weaker lens is required than is indicated by this expression. In the same way as for the anterior lens surface I have applied the formula for conjugate points to asymmetry of the posterior surface in simple astigmia, in hyperopia of 5 D and in myopia of 10 D, and I have found that *nine-tenths* of the astigmia as measured by the expression

$$\frac{1}{F_2} - \frac{1}{F_1}$$

approximately represents the power of the correcting lens in all of these conditions. The scale of my ophthalmometer has been constructed in accordance with these findings.

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